SEDIMENTARY STUDIES IN ~~THE NORTH BASIN~~ LAKE ~~OF~~ WINDERMERE.

by

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ABSTRACT.

Late Quaternary sediments, soils, and parent rocks in and around the Windermere North Basin are studied by modern sedimentological techniques. The data obtained is examined statistically.

Till points, scattered randomly on the sand/silt/clay triangle, were redistributed into a "still water group", glaciolacustrine clays and main Windermere sediments; and a coarse fluvioglacial group which is better sorted and more rounded than the till. Fine sands, negatively skewed due to finer admixtures, typify certain lake environments. Beach deposits are better sorted and more rounded than the till from which they were partly derived; they are more rounded and coarser on the eastern exposed beaches than on sheltered ones; they are positively skewed due to inefficient fluviatile saltation.

Three assumptions:

a. Flocculation caused real mechanical bimodality of organic sediments.

b. Spasmodic sedimentation was by underflowing "turbidity" currents during storms.

c. Deposition occurred when settling (discrete or floc--ulated) overcame mechanical dispersal.

Loss of river water impetus, and organic content and biological activity, controlled Post Glacial sedimentation. The relative importance of the two main rivers has alternated.

Two basic mineralogical populations formed Late Quaternary material:

a. Potassium rich clay. Pink Late Glacial form, non hydrated. Post Glacial form, illite and aluminosilicates, hydrated and flocculated due to organic content and acidic environment (occurs up to 0.020 mm).

b. Silt. Chloritic rock fragments (magnesium rich ripidolite, iron rich thuringite); calcite was removed from all but buried varves by Post Glacial acid corrosion.

A marked change in lake sedimentation occurred with the spread of plant growth at the end of Late Glacial times 11,000 years ago. Controlled erosion, flocculation, and a high organic content characterised Post Glacial reddish gyttja sedimentation. Human settlement in the last 200 years caused further changes: accelerated erosion due to forest removal, reducing lakewater conditions due to sewage caused stronger flocculation in the blackish surface ooze.

Preface.

The list of contents on page 7 is complete and a selective reader may be guided by these. Here it is emphasised, however, that much of Part II is purely des--criptive of methods and apparatus. This is given with the thesis for specialist reading because the methods were often ad--apted from standard usage for these flocculating fine grained sediments sufficiently to require explanation. All modificat--ions have been tested and the tests are presented. The triang--ular diagram in Chapter 17 is important but it is placed there for the purposes of reducing the multifarious data from Part II A and B to a manageable state.

Part III is important for detailed sedimentological studies in Windermere; particularly a general discussion in Chapter 20, the figures and tables with Chapters 21 and 22, and the summary in Chapter 23.

Part IV comprises the qualitative analyses, methods, interpretations, and summaries. Thus Chapters 24, 25, 26, and 27 are descriptive. Chapter 31 is a particularly important summary.

Part V, the summary of the conclusions,does not list the detailed conclusions. Two important considerations, however, from Parts III and IV are mentioned most appropriately here for wider application.

Some of the work is repetitive but there is an adequate cross referencing system. The thesis has been prepared in acc--ordance with the rules suggested by Hough and Cropp (1958).

This quantity of work would have been impossible with-out the full time assistance of Miss C. Graham.

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CONTENTS.

PART I. INTRODUCTION.

Chapter 1. Geological History of the Area.

Lake District.

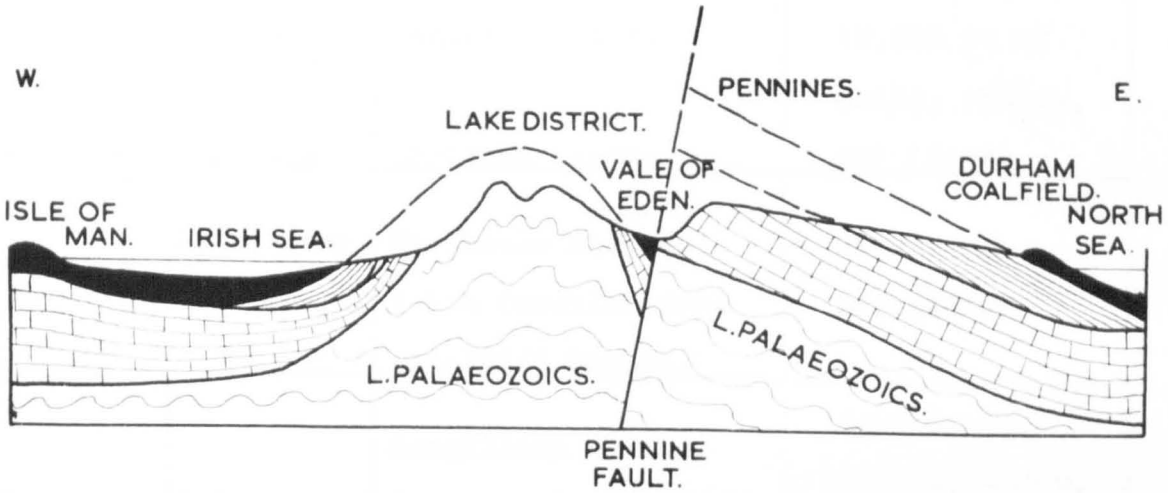
The English Lake District is a Lower Palaeozoic inlier fringed mainly by Lower Carboniferous rocks which dip away from the centre of the area. It covers more than one thousand square miles (2590 sq. km) of the North Western counties of England. It is separated from the main North - South Pennine chain by the Pennine Block Fault system which runs North - South along the line of the Eden valley (fig. 1). Permo - Triassic and Lower Jurassic rocks along the line of this fault suggest that the Lake District was downthrown to the west during the Armorican movements at the end of the Carbon-iferous. The dome structure (fig. 2 a,b) was imposed on the area, which may then have been covered by Mesozoic rocks, during the Middle Cretaceous (Hollingworth, 1954). Since then, Post Lower Palaeozoic rocks have been eroded off the inlier, leaving superimposed radial drainage on the hard ancient core (fig. 3).

The Lower Palaeozoic rocks (table 1) are of geosynclin-al facies accompanied by several major granite intrusions. They have an E.N.E. - W.S.W. strike (fig. 3) and they are a part of the major Caledonian geosyncline which extended from Wales to Scandinavia. The area was uplifted in the mid - Miocene when river erosion became important and caused a series of river terraces to be formed which are preserved in places in spite of subsequent ice action (Hollingworth , 1937). Thus it formed an area of hard uplifted rocks of subdued relief during the Pleistocene ice ages and it now exhibits topographical

Figure 1. General Geological Map of North - West England, showing Lake District and smaller Lower Palaeozoic Inliers.
(Mainly taken from Wells and Kirkaldy, 1937)

a. General East - West Section acro-ss Northern England, showing relations of the Lake District.

(Approximate line of section in figure 1)



b. General North - South Section across the Lake District.

(Approximate line of section in figure 3)

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Figure 2. Sections across the Lake District area.

(reproduced from Eastwood, 1953)

Table 1. Stratigraphic Table of Lower Palaeozoic Rocks in the Lake District. (after Hollingworth, 1954)

SILURIAN.	Ludlow.	Bannisdale Slates. Coniston Grits.	Rapid Deposition: 12,000 ft of grits, shales, and flags.
	Wenlock.	Coniston Flags.	
	Llandovery.	Stockdale Shales. (with fossiliferous Skelgill Beds).	Slow Deposition.
	Bala.	Ashgillian Series. Coniston Limestone.	Limestones, shales, tuffs, and local lavas.
Unconformity.		(mainly derived from volcanics)	
ORDOVICIAN.	Lower Llandeilo. Upper Llanvirn.	Borrowdale Volcanic Series.	Lava, tuff, and agglomerate sequences[1]. (some shales)
	Lower Llanvirn. Arenig. Tremadoc.	Skiddaw Slates. (base not seen)	Several thousand feet of marine grits and flags.

1. The detailed structure and stratigraphy of the Borrowdale Volcanics is confused due to the repetitive nature of the lava/tuff sequences. Hartley (1925)[1], Mitchell (1929)[2], Konig (personal communication, 1962)[3], and Pink (in preparation) have examined different parts of the outcrop and they agree only on broad points in areas where they overlap.

1, 2. CITED BY HOLLINGWORTH (1954).

3. THESIS IN PREPARATION.

Figure 3. Geological Map of the Lower Palaeozic Rocks of the Lake District Inlier; Showing S.S.W. Strike, the Axis of the Dome and Radial Drainage.
(Mainly taken from Wells and Kirkaldy, 1937)

features typical of a region where glacial erosion has been intensive such as overdeepened valleys, many of which now contain long narrow lakes. Windermere is the largest of these (Marr, 1916; Hollingworth, 1954). After the last period of erosion drift accumulated in the valleys and varved sediments in the lakes during the Late Glacial. The Post Glacial sediments which followed contained organic detritus. Late Glacial deposition is dealt with more fully in the following section. The Post Glacial sediments in particular, and the varves, are the main topic of the present study.

General Late Quaternary Principles of Deposition and Terminology, with special reference to Windermere Deposits.

(General references on the Late Quaternary: Wright, 1937, p.27; Flint, 1947, p. 103; Charlesworth, 1957, pp. 360,361, 435 to 437, 465, 504 to 506. A suitable terminology for Windermere was generally taken from these, though sometimes it was adapted.)

The last ice cap in the Lake District started to recede 12,000 years ago so this is the beginning of the Late Glacial (Pennington, 1943, 1947a). Its melting resulted in an accumulation of drift, including ground moraines or Boulder Clay within the area of the ice, and outwash plain or fluvioglacial deposits within extraglacial areas, marginal or subglacial. The latter is a general term applying to stream deposited sands and gravels and to glacio - lacustrine clays deposited in "ponded" water; they are apparently "normal" deposits (Pettijohn, 1957, pp. 266 to 275). Some valleys were blocked by terminal moraines.

The moraines or boulder clays are unstratified deposits consisting of unsorted fragments and with a "millionfold size range" (loc. cit.). About four fifths by weight forms the matrix

and about a half is clay. The matrix is a paste of unaltered rock material incorporating sand, pebbles, and boulders indiscriminately (loc. cit.). The lack of altered material suggests that ice erosion cut under the weathered mantle to the solid bedrock of the valleys. These unsorted and unstratified deposits may be formed by mud flows, solifluxion, or landslides, so the distinctive characteristic of ice transported boulder clays is the presence of faceted and striated "cobbles" (loc. cit.). Ideally boulder clay is formed without the cooperation of water but actually size sorting is present to an indefinate degree in deposits to which the term is applied due to the inevitable presence of a quantity of meltwater.

The outwash plain or fluvioglacial sediments were formed by meltwater. This latter was present for a long period on, in, and under the ice at the terminal zone of a glacier and it washed the boulder clays of some finer grained rock material during or even before its deposition by the ice. When this effect is especially marked, the ice deposits pockets of an unusually coarse residuum. Aqueous activity was particularly vigourous in the Late Glacial; the climate was moist and there was meltwater being released, the ground was frozen, and evaporation was at a minimum due to the cold. Thus the increased run off in the swollen rivers was concentrated into a few summer months. Apart from aqueous activity, frost, avalanches, and solifluxion were defacing agents; they were all modifying a landface bare of vegetation and covered in thick drift. Even rock barriers in the valleys ("threshold" region of Windermere, see next section) were not excavated by the streams at first due to the thick drift cover. This vigourous activity caused rapid mass movement from areas

vulnerable to erosion, generally the higher ground, to areas of deposition such as "ponded" temporary lakes, which were rapidly filled, and the main lakes where thick varved sequences accumulated. The changing conditions due to melting ice caused a great diversity of these fluvioglacial sediments rapid changes of facies and localised extent of beds. These deposits are noted for their heterogeneous grain sizes and degrees of sorting; also for their graded nature so that unsorted boulder clay may have passed into poorly sorted gravels and sands, which in turn passed rapidly downstream into, and were also buried under, better sorted finer material.

After most of the ice had disappeared from the main valleys "Lacustrine Deposits" showing summer/winter (silt/clay) varved stratification started to form in the lakes they then contained. Ice rafted erratic pebbles ("Pebble Bands") found within the varved sediments indicate that occasional "icebergs" still occured floating in the lakes (Windermere, see Chapter 5). Pettijohn (1957) claims that these rafted blocks, large or small, constitute among the most conclusive evidence for glacial activity. A further feature, in Windermere at any rate, is the existence of special sequences found under the flat lying regions near the two larger river inlets (Brathay, the main inlet, and Troutbeck, see next section) in which dark grey "silt" overlies pale plastic clay fairly sharply. The clay was certainly deposited in ponded conditions probably when stagnant ice in the main lake valley caused the river water to be dammed temporarily. This facies is thus glacio - lacustrine (Smith, personal communication, 1960). The "silt", however, is too coarse to have been deposited in ponded conditions (Chapter 17) and one possibility is that it

represents a "mud flat" stage (alluvial) when the lake was at a higher stage than at present; and it is either Late Glacial or Post Glacial in age. Due to this uncertainty this sequence was not referred to as fluvioglacial but termed "Deltaic" silt and clay for convenience. It is emphasised, however, that they are not of true glacial deltaic facies (current bedded sand silt, and frequent coarser material).

The beginning of the Post Glacial is well marked in the lake sediments (Pennington, 1943, 1947a) by a sharp transition from varves to organic detritus, though occasional clay bands persist through the early Post Glacial "transitional facies". The beginning of the Post Glacial is not well marked in material other than deep water lake deposits. For instance it is not known whether the deltaic silt was formed before or after the end of the varved sediments in the lake. The rates of accumulation have been comparatively rapid during the Post Glacial (lakes: Pennington, 1943; beaches: Marr, 1916). This is because rivers were cutting down fast in their high coarses; they were recovering from arrested development due to overloading at first.

Windermere.

(A feature map of the catchment area is in fig. 4)

Windermere is the largest lake in the Lake District, spanning its southern margin. It is approximately 11 miles (17.7 km) long and 1 mile (1.6 km) wide at its widest point. Its general trend is north - south, following the main radial drainage pattern (fig. 3). It was a pre glacial river valley which has been excavated and emphasised by glacial erosion. This valley does not follow a fault pattern for all of its length in contrast to the majority of lakes in the district (Ward, 1875). The present

Figure 4 is to be found folded in at the back of this volume.

lake fills two overdeepened long rock basins, separated by a shallow rocky "threshold" with numerous islands of which Belle Isle is the largest. Glacial erosion is suggested here by the fact that the deepest part of the lake is near the main ice inlet at the north end (Marr, 1916). Three miles (4.8 km) of the the northern basin is beneath sea level (Ward, 1875); it is 67 metres (220 feet) from the top of the sediment to the water surface at its deepest. The terminal moraine at the south end of the lake, in the vicinity of Lake Side and Newby Bridge, accumulated at the last maximum of glaciation. It was only reduced to its present outlet level at a comparatively late stage by the River Leven (Marr, 1916). Previous to this the lake level was considerably higher than at present as is suggested by the old beach platforms, at about 25 feet and 5 feet above the present lake level, found in places near the lake shore (Smith, personal communication, 1960). The natural dam formed by the moraine, and probably some stagnant ice as well (Hollingworth, personal communication, 1962), at the lower end of the lake yielded suddenly and the lake level dropped at least twice in a comparatively short time. If this should happen again to the extent of 15 feet (4.57 m) the lake would be divided into the two basins by the present "threshold". This study is devoted to the deposits on this "threshold" and to those in the northern basin, termed the North Basin of Windermere.

The head of the lake is near to the centre of the Lake District, a region of high ground, steep sided valleys, and intense glacial activity. The main inlet, entering the lake by way of a wide delta, is a combination of several rivers

flowing in glaciated valleys north of the lake. The delta is encroaching onto the lake as is demonstrated by the site of the Roman Fort at Waterhead; this is thought to have been built at the water's edge but it is now about 300 feet (91.4 m) away. Further south the lake is surrounded by an area of decreasing altitude typical of one where a glaciated mountainous region merges into the coastal plain, the latter being the Morecambe Bay lowlands stretching for about 10 miles (16.1 km) south of the southern end of the lake. A second major inlet stream enters the lake half way along the eastern side of the North Basin. This has its source in the high ground to the north and it also flows into the lake by way of a wide delta. Numerous other short and torrential streams enter the lake in a fairly uniform distribution.

The Windermere Ice Cap. (fig. 4)

The ice in the Lake District is thought to have covered the highest peaks when at a maximum (Marr, 1916) and so, in fact, the lakes are shallow compared to the ice which filled them (Ward, 1875). The importance of interglacials and interstadials prior to the last major glaciation is not known (Marr, 1916). The ice in the Windermere basin was almost entirely local in origin so that the snow from which it was formed fell within the limits of the present catchment area (Greswell, 1950). Ice movements within the Lake District as a whole are shown in figure 5. It is in-ferred that glaciers in the main valleys to the north, Brathay, Great Langdale, Rothay, and Stock Ghyll, combined in the region of Ambleside to form the main Windermere ice. The resultant of the individual forces created by these glaciers was in a S.S.E. direction (Ward, 1875) and so there steep slopes to the heights East and South East of Ambleside and the lake at this point

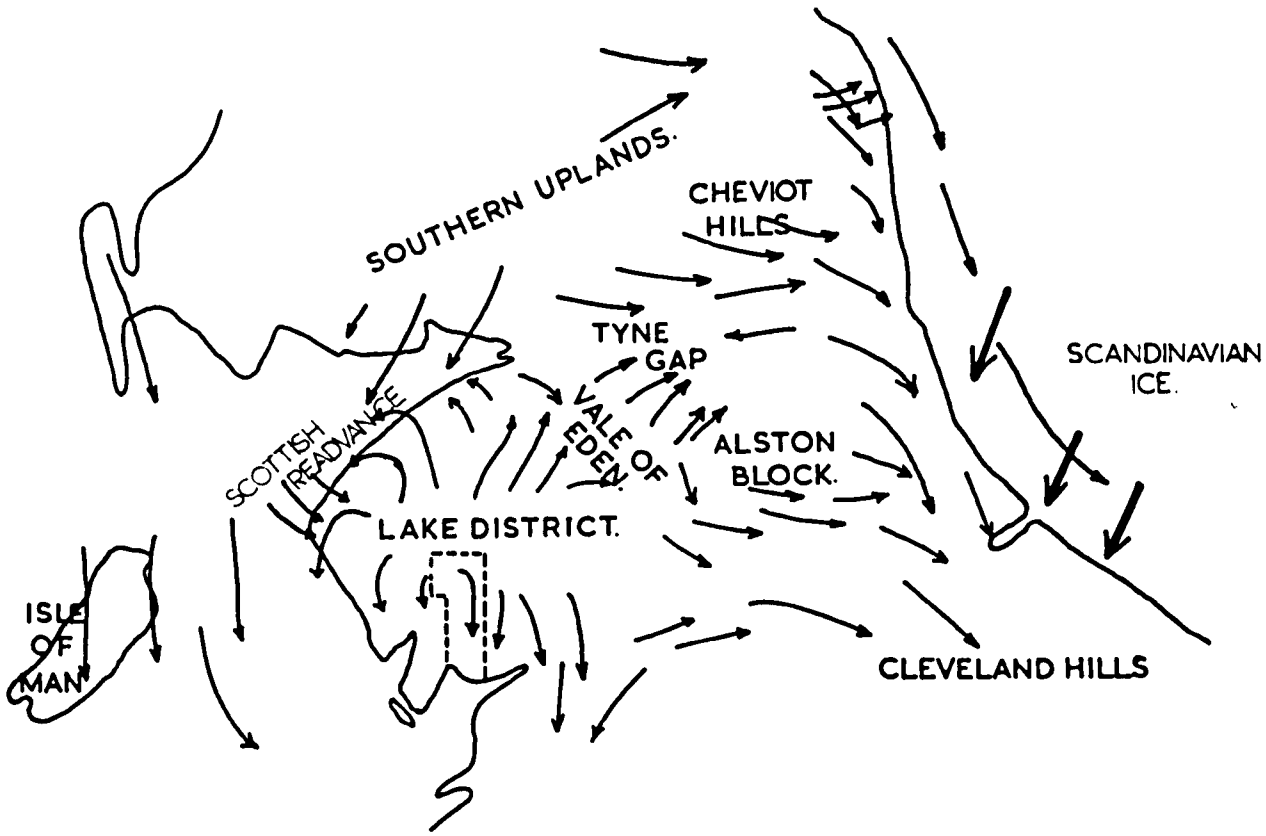


Figure 5. Directions of Ice Movement in Northern England and Southern Scotland.

(reproduced from Eastwood, 1953)

trends S.S.E. A minor portion of this northern Windermere glacier was diverted to the S.S.W., through Hawkshead and Esthwaite west of the Claife Heights, and rejoined the main Windermere ice through Cunsey Beck valley south of Sawrey. South of this diversion in the main valley the ice rode over the central "threshold" region; striated pavements on the islands here indicate a nearly due south movement of the ice at this point. There have been several theories postulated for the origin of this shallow region. Ward (1875) says that it may be due to the widening of the valley at Bowness and the resulting decrease of erosional force in the ice. Greswell (1950) follows this up by saying that the southern basin is deepened as a result of the Esthwaite ice rejoining the main ice and fortifying its erosional powers. Ward suggests as an alternative that there were pre glacial rocky hills at this point. Hollingworth (personal communication, 1962) says that this is typical of the "wavy" motion of ice erosion in a valley. In the basin south of Trout-beck the ice was no longer confined to a narrow valley and it started to spread out over a wider area losing considerable force as it did so. There are drumlins on the east side of the lake at the Troutbeck delta and south of it.

The present work examines further details of the morph-ological evolution of the basin after this last ice cap started to recede.

Present Day Topography. (fig. 4)

The Coniston Limestone outcrop, a well marked horizon about 100 feet thick (30.5 m) at the top of the Ordovician, crosses the lake just south of Ambleside. North of this limestone, the topography is rugged due to the varied nature of the Borrow-

-dale Volcanics and the numerous shatter belts (Marr, 1916). To the south the Silurian rocks give rise to both a smoother and a lower lying topography due to their more uniform lithology and to the fact that, being on the southern margin of the dome, the rocks here were not uplifted to the same extent as those further north.

Present Day Drainage System. (fig. 4)

The rivers of the main inlet system which flows into Windermere at Brathay delta cross Borrowdale Volcanic rocks only. Troutbeck has its source on these rocks but crosses the limestone and flows over Silurian rocks before entering the lake. Numerous short streams entering the lake south of the Coniston Limestone generally flow exclusively over Silurian rocks.

The small lakes in the Windermere catchment area, apart from the high tarns, are on the courses of the main rivers acting possibly as sediment traps. Grasmere and Rydal Water on the River Rothay, and Elterwater, at the junction of the rivers Brathay and Great Langdale Beck, were studied in this respect.

Present Day Soil and Vegetable Cover. (Stamp et al, 1943)

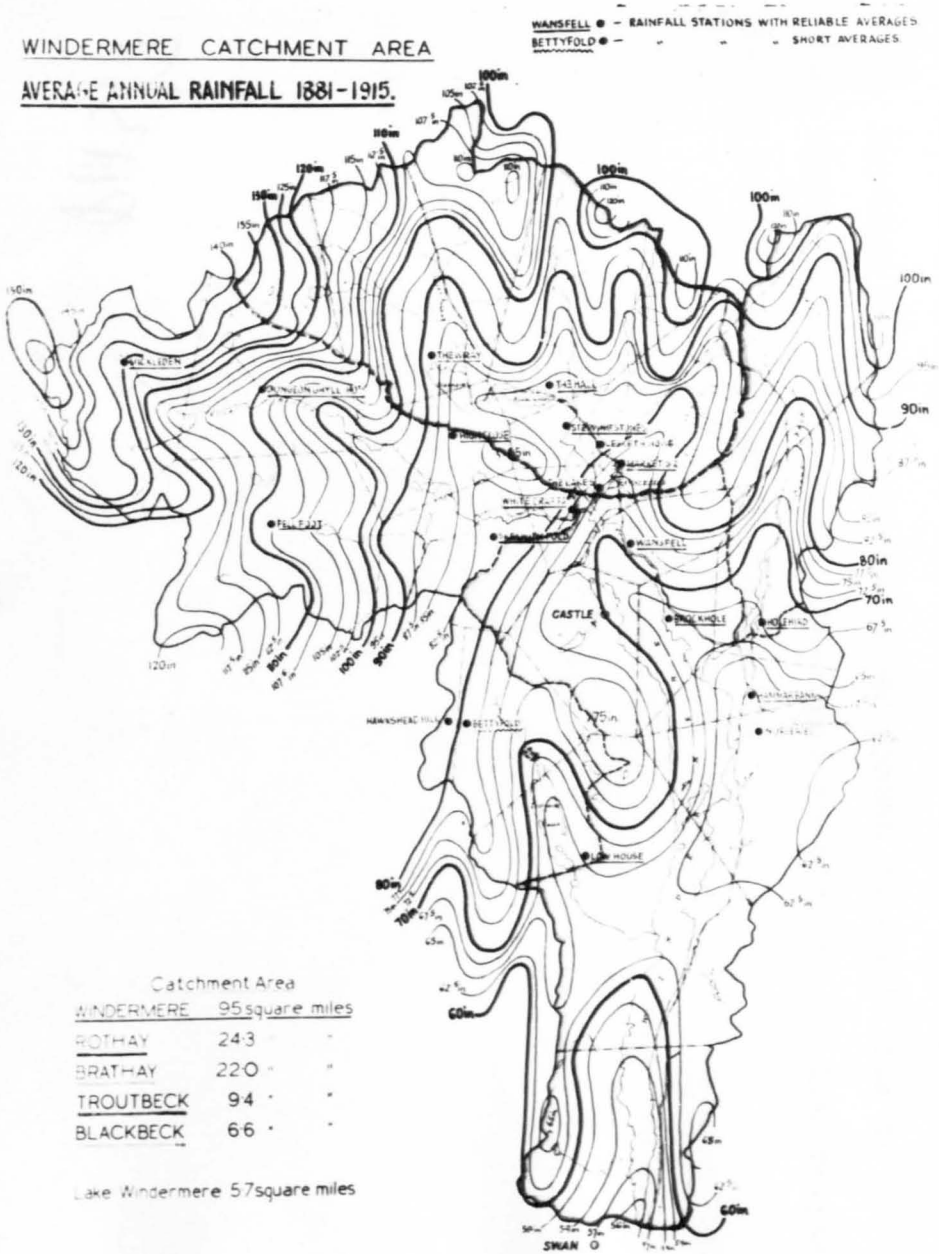
The distribution of the soils and vegetable cover in the Windermere catchment area is largely controlled by the extent of the glacial drift. This tends to fill the larger valleys which were eroded by the glaciers during the ice maximum, and to leave comparatively bare the higher ground. The main rivers follow these valleys leaving a veneer of alluvium covering the glacial deposits in the vicinity of their courses. The "mountain soils" are shallow with an irregular profile due to spasmodic interruptions of rock outcrops and hill peat. These soils support grass throughout, heather below 2000 feet (609.6 m),

and trees below 1500 feet (457.2 m); the area has been extensive--ly afforested up to this height . The "moorland acid peat" is local in occurence; extreme podsolation and consequent waterlogg--ing are causing comparatively pure peats to be formed at present.

The "forest soils" in the low ground are mainly based on the extensive glacial drift filling the valleys; these are podsol type. The parent material ranges from stiff clay to boulder masses in a matrix of sand and clay. The overlying soil shows corresponding variations which are indicated by the topo--graphy. These factors lead to a wide range of drainage condit--ions with clayey waterlogged hollows and sandy dry hummocks, for example in the Troutbeck region near the lake shore. Gener--ally it may be said that these drift soils are stony loams. The soils which are based on the river alluvium are also loamy. These "forest soils" on low lying areas generally support perman--ent grass though afforestation often extends down into this belt from the higher ground. A small amount of the alluvial soil that is in no danger from flooding supports ploughed arable land. There are extensive areas of peat on low ground in parts of the Lake District; these are now decreasing in area to give light black soils on the margins and they support "mild peat soils" in contrast to "moorland acid peat". It is not certain whether any of these tracts occur in the Windermere catchment area.

Present Day Climate. (Stamp et al, 1943)

The precipitation in the catchment area is extremely variable from place to place. For example there are 150 inches (381 cms) per year in the Langdale Pikes and 65 inches (165.1 cms) only twelve miles away (19.3 km) in Sawrey (fig. 6a). The precip--itation is fairly uniformly distributed over the year, slightly



b. Reproduced from Phillips' Atlas.

a. Rainfall Map.

(Photograph supplied by F.B.A.)

Figure 6. Climatic Diagrams.

more falling in the winter months than in the summer (fig. 6b). Snow falls are most likely between December and March; snow lies for an average of ten days in the year on ground lower than 500 feet and for over three months on the high summits. There are about eight days of thunderstorms per year, mostly in the summer.

The temperature is also variable from place to place. The average January temperature in the low lying area at the southern end of the catchment area is 41°F (5°C) whilst in the high ground north of the lake the temperature remains below freezing point for several months, at this time a distinct "snow line" can be observed. The average July temperature in the low ground is 60°F (15.6°C); in the high ground it is 52°F (11.1° C). Variation between the two extremes depends mainly on altit--ude. Daytime variation in the high ground is small due to strong winds or to low cloud. Seasonal variations at Seathwaite, further north, are shown in figure 6b.

Studies of Windermere Sediments.

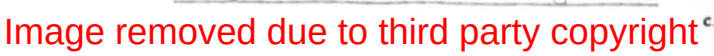
Biological Studies.

Present day sediments in the lakes of the Lake District have been the objects of a considerable amount of biological study; the earlier lake sediments, Late Glacial deposits and "gyttja", have also been examined in this respect; by members of the Freshwater Biological Association and associated authors. Pennington (1943) has described large and small diatom assemblages from all lake sediments above the boulder clay ("stony clay"), with reference to possible stratigraphic sequences, particularly Asterionella whose "burst" in the "surface ooze" is said to be caused by the sewage matter in the lake resulting from human settlement in the last 200 years. The same author (1947a) has also described pollen assemblages from the same sediments with special reference to zoning (fig. 7 a,b, reproduced from Penning-ton, 1947a). This aspect is considered in greater detail in the next section. The same author (1947b)has also summarised the diatom, pollen, and chronological sequences in Windermere (fig. 7c, reproduced from Pennington, 1947b), making the assumption that rates of deposition have remained constant throughout the Post Glacial period. It is noted that climatic and biological conclus-ions here correlate closely with work in Esthwaite (Franks and Pennington, 1961), the Lake District as a whole (Walker, 1955), the British Isles (Godwin, 1948), and North West Europe.

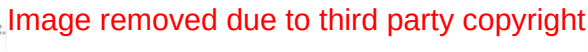
Stratigraphical Studies. (To be read with figure 7; 7d is reproduced from Pennington, 1947a; and table 2. Table 2a summ-arises Pennington's pollen zones, table 2b summarises late Glacial and Post Glacial sediment nomenclature used in this work.)

a. Shallow Water Pollen Diagrams.

b. Deep Water Pollen Diagrams.



c. Generalised Correlations.



d. Stratigraphic Section.

Figure 7. Correlation Diagrams Reproduced from Pennington, 1947 a, b.

Table 2a. List of Pollen Zones. (after Pennington, 1947a)

	VII.	(*Quercus* and *Alnus* Zone.)
	VI.	*Pinus* - *Corylus* Zone.
		a. *Betula* dominant.
POST - GLACIAL.		(b. Obscure in Windermere.)
		c. *Quercus* and *Alnus*.
	V.	*Pinus* Zone.
	IV.	*Betula* - *Pinus* Zone.
	III.	Upper Laminated Clay: Total Pollen sparse and *Pinus* relatively abundant.
LATE - GLACIAL.	II.	Grey Detritus Silt: *Salix* and *Betula*; equivalent of Alleröd temperate deposits of North - West Europe.
	I.	Lower Laminated Clay: Pollen absent.

"Stony Grey Clay"

Table 2b. Late Quaternary Deposits and an introduction to the stratigraphic terms used in this study.

		"Shoreline" Deposits		Lake Deposits
POST GLACIAL	Present - Day Material; liable to transport and redeposition.	Beach Material	Near - Shore Silts	Surface Ooze (or Asterionella Ooze; Pennington, 1947a)
	Post - Ice Influence.		Clay bands near river mouths	Gyttja (loc. cit.) Transitional Clay/Gyttja (loc. cit.)
LATE GLACIAL	Post - Ice Maximum. (SO < 3.0; except lake pebbles.)	"Fluvio - Glacial" and "Deltaic" Deposits. (clay, silt, sand and pebbles; laminated or unlaminated.)		"Lacustrine" Deposits. (including sand, silt and clay laminations; and some pebbles.)
	(SO > 3.0).	Soils and Boulder Clay		
		Glacial Erosion Surface of Lower Palaeozoic Rocks.		

N.B. Statistical justification for subdivisions given in Chapter 17.

Pennington (1947a) has shown the existance of the an interesting relationship between pollen assemblage zones, which are taken to represent time boundaries, and the sequence of sediment types in Windermere.

Above the "stony clay" in all parts of the lake outside the region of wave action (greater than 5 metres), there occurs a laminated (stratified) clay facies ("lacustrine" deposits in table 2b) representing a climatic period when the lake was frozen in winter (clay layers) and thawed during the summer (silt layers). It is claimed that there is evidence for correlation, by de Geer's method of counting the varves, between Windermere and Scandinavia; although practical difficulties were met by the author. It is postulated that the laminated clays in Windermere can be subdivided into the pollen zones I, II, and III, of which zone III material has been penetrated in deep water (greater than 20 metres), this is shown in figure 7b. All three zones have been recognised in shallow water cores (less than 10 metres), this is shown in figure 7a. Zones I and III represent a cold climate though slightly warmer towards the end of III as indicated by the appearance of Pinus pollen; zone II indicates the occurence of a warmer period ("interstadial") because of the organic detritus and silty nature of the deposit and because of the appearance of Betula and Salix pollen. This zone is thought to be equivalent to the Alleröd temperate layer of North West Europe, though the contemporaneity of the various appearances of this deposit is still uncertain. On the steep slope between shallow and deep water, zone I clays appear unconformably beneath later deposits.

The silty organic detritus of the Post Glacial period in Windermere takes the form of a reddish brown mud termed

gyttja. Between this and the laminated clays of the Late Glacial period there is a transitional facies in all parts of the lake except the steep slopes between deep and shallow water. The transitional facies consists of the gyttja material with frequent clay bands. The base of this sequence is contemporaneous in all parts of the lake, representing the disappearance of the influence of intense glacial activity last represented in zone III; in fact it represents the beginning of the Post Glacial period. However, zone IV, in which the appearance of abundant Betula pollen indicates a warmer climate, contains the entire transitional sequence in shallow water (fig. 7a); whereas it only contains a very narrow layer at the base of the same facies in deep water (fig. 7b). Here the transitional deposits also occur within zones V and VI. The gyttja above this is marked off sharply from the transitional facies in deep water by the topmost of the clay bands, which is comparatively prominent and is thought to be a distinctive stratigraphic horizon. The gyttja occupies zones V, VI, and VII in shallow water and zone VII only in deep water. In the zone VII deposits in shallow water (fig. 7a), there appear to be narrow clay bands with a distinct relationship to nearby stream mouths, none of these were found in this study. Above zone VII in deep water and overstepping unconformably across zones VII, VI, and V in shallow water, the black "Asterionella surface ooze" is being formed at present.

The unconformity beneath the surface ooze and, possibly, others above the top of the laminated clays in shallow water which have not been detected, are due to the spasmodic dropping of lake level in Post Glacial times (Chapter 1), and to the resulting erosion of unconsolidated deposits newly brought within

the zone of wave action. The unconformity on the steep slope between shallow and deep water (where material in zone VII is found lying directly above zone I clays) is due to slumping of sediment down this slope under gravity (Smith, personal communic--ation, 1963). The later appearance of clay bands in the deep water transitional facies (zones V and VI), than of those in shallow water, is thought to be due to erosion of slump exposed clays from the steeper slopes into deep water; and not due to climatic factors (loc. cit.).

Sedimentological Studies.

Smith (1959b)has described some of the slump structures in the laminated clays of Windermere, though no final conclusion has been postulated as to their mode of origin. Mackereth (person--al communication, 1963) has studied the chemistry of the water and some of the sediments in Windermere.

Limnological Studies.

Mortimer (1952) has described the effects of stratific--ation and autumn turnover as applied to Windermere. The lake has three layers in summer:

a. Hot Epilimnion at the surface.

b. Cold Hypolimnion near the lake floor.

c. Thermocline : the fairly sharp thermal gradient between the two.

Autumn winds blowing along the length of the lake cause the "turnover" until the lake becomes uniform throughout the winter. In the spring, rising air temperature heats the water surface and stratification starts again. Trask (1951) says that the critical temperature in both spring and autumn is 39°F (3.9°C). The

hypolimnion in Windermere remains at the same temperature during the summer as the entire lake was just prior to stratification; it is almost completely isolated from activities near the surface.

Pearsall (1920) and Hutchinson (1942) have postulated evolutionary sequences of events for lakes in general. Pearsall has placed those in the Lake District in order of maturity. Hutchinson favours lake evolution in a series of sharp changes until a state of "trophic equilibrium" is reached early in Post Glacial history, after which only human factors can fundamentally alter the status of the lake. Pearsall favours gradual and continuous change and has placed Ennerdale and Wastwater at the "primitive" end of the scale, saying that they may eventually attain the status of Windermere.

Studies of Sedimentation in Confined Basins.

It is of interest to examine previous work on recent sediments in confined basins other than Windermere. Much has been published in this respect and a sample of relevant work is given mention here.

Trask (1951)discussed the connection between limnology and the study of lake sediments and emphasised that the sediment is influenced by the lake water. The critical factors are:

a. Temperature extremes.

b. Rainfall and its seasonal (and cyclic) distribution.

c. Average temperature of the water.

d. Presence and type of micro-organisms.

e. Dissolved material.

f. Size, shape, and depth of the lake.

g. Supply of detritus.

Factors of temperature and density affect organisms which, in

conjunction with dissolved minerals, affect organic productivity, redox potential, and hence sulphide formation. Lakes with summer stratification are likely to be well oxygenated, though deep water lakes are not affected by storms to the same extent as shallow ones. Discussing sediments, Trask generalises that, near shore-lines and deltas, deposits are likely to be highly variable; while in deep water they may be well stratified.

Eakin (1936) says that the rate and distribution of sediment accumulation depend on the quantity and character of the sediment particles transported by incoming streams "below the flow line" of the lake (or reservoir); these are determined by:

a. Extent of watershed area.

b. Climatic erosional factors.

c. Topographic relief.

d. Soil cover and its protection by vegetation.

e. Land use in the watershed area.

Any variation in one or more of these factors is accompanied by a corresponding change in the stream load. The latter is also liable to vary on its own due to:

a. Physical and chemical attack on the particles.

b. Load/alluvium exchange and accompanying sediment volume alteration.

In the lake itself silting processes are dependant upon settling rates and "mass effects" of the different stream load size fractions, only the finest size grades will be carried over at the downstream end. Deltas are current bedded, stream borne, coarse material only so that if there is no coarse material, there is no delta;.and if there is no fine material the delta is the only region of deposition. Fine material is spread out broadly

over the lake floor, though it tends to accumulate most thickly in the deepest parts. The author postulates that this effect is due to gravity acting on a dense "silty turbidity current" under-flowing the less dense desilted water above. Eakin, in conclusion, states that the ratio of sediment deposited to incoming sediment increases with increasing "storage capacity", and that rates of erosion in watershed areas are increased by the fact of human settlement.

Murray (1956) has studied three comparatively small lakes in Wisconsin: Mendota, Trout, and Wingra Lakes. In Mendota, there is a sequence of deposits similar to that of Windermere, with black "sludge" (= surface ooze) grading sharply down into "buff marl" (= gyttja). These sediments contain carbonates in contrast to those in Windermere; the marl contains, on average, about twice as much carbonate as the sludge, probably through elimination of sulphide and organic matter by micro-organisms and bacteria. Murray, however, considered that the two are separate deposits showing a normal stratigraphic relationship. Deevey (cited by Murray) postulated that this sudden change in sedimentation was due to reduction of carbonate entering the lake. But Murray suggested that the change is unlikely to have been so sudden and said that Lake Wingra is in an apparently similar drainage basin but the uppermost deposit there is buff marl. He postulated that the reasons for the change were:

a. Recent agricultural developments in the Mendota basin removed much of the natural protection there and a fairly sudden increase in clastic material entering the lake took place.

b. The building of Madison City on the shore and the dam at the lower end of the lake caused changes in lake chemistry

and an increased organic productivity. Mendota is a naturally stratifying lake and the increased organic productivity in the epilimnion during the summer months caused an oxygen deficiency in the hypolimnion because there was little water exchange across the thermocline. Thus there tended to be a euxinic reducing environment on the lake floor in which iron is in the ferric state. Certain bacteria produce sulphides under these conditions and the resulting ferrous sulphide gives the black colour to the sludge. The clastic carbonate would tend to be dissolved in this environ-ment and, as it is not entirely decomposed, it is inferred that the environment is only weakly reducing; the autumn turnover oxygenates the lake during the winter.

His conclusion is, therefore, that organic matter and carbonates remain constant but that clastics and organic product-ivity increase over the sludge/marl boundary. It is noted that Lake Wingra is smaller, its watershed area is not developed to the same extent, and it is a non stratifying lake; it is signific-ant that the sediment produced here at present is buff marl. Trout Lake is limnologically similar to Mendota, though smaller. A further implication of the recent changes in Mendota is describ-ed as the secondary effect of "morphometric eutrophy". Here the increased clastic input decreases the hypolimnion volume and emphasises the oxygen deficiency. The early Mendota sediments show gradations from varved clay to organic deposits, similar to those in Windermere except for the high carbonate content throughout, and especially dolomite.

N.B. There is much previous work by other authors which is relevant to this study of Windermere but not mentioned here; these references are found in the appropriate chapters.

Chapter 3. Methods of Study.

The Purposes of the Work.

This study attempts to be comprehensive, applying the methods of sedimentary petrology to samples of the wide range of sediment types, chiefly unconsolidated, which occur in the Windermere basin. There are two main directions in which conclus--ions are drawn from the resulting data.

1. The Sedimentary History of the Basin in the Late Quaternary. This aspect includes:

a. A classification of the Late Quaternary deposits on a basis of environments of deposition leading to the morphological evolution of the basin during this period; especially in conjunct--ion with geophysical data and the few geomorphological observat--ions available.

b. A detailed grain size study of sediments sampled from Windermere lake itself, both Late Glacial and the organic rich Post Glacial deposits, leading to the physical processes of lake deposition and the evolution of these processes from fairly early in the Late Quaternary. Thus it is shown that grain size, organic content, and flocculation have increased throughout the Post Glacial; and that throughout the lake's history grain size (also flocculation and organic content in the Post Glacial) has decreased downstream from the two main inlets; also that these two appear to alternate in ascending order of vigourous activity.

c. Comprehensive qualitative analyses leading to the miner--als in the rocks and in the sediments, representing the progress--ive stages of Late Quaternary evolution; and to the equivalent weathering processes and generalised environments of chemical alteration.

2. Some methods and thesis conclusions which may have wider applications than the Windermere basin, these include:

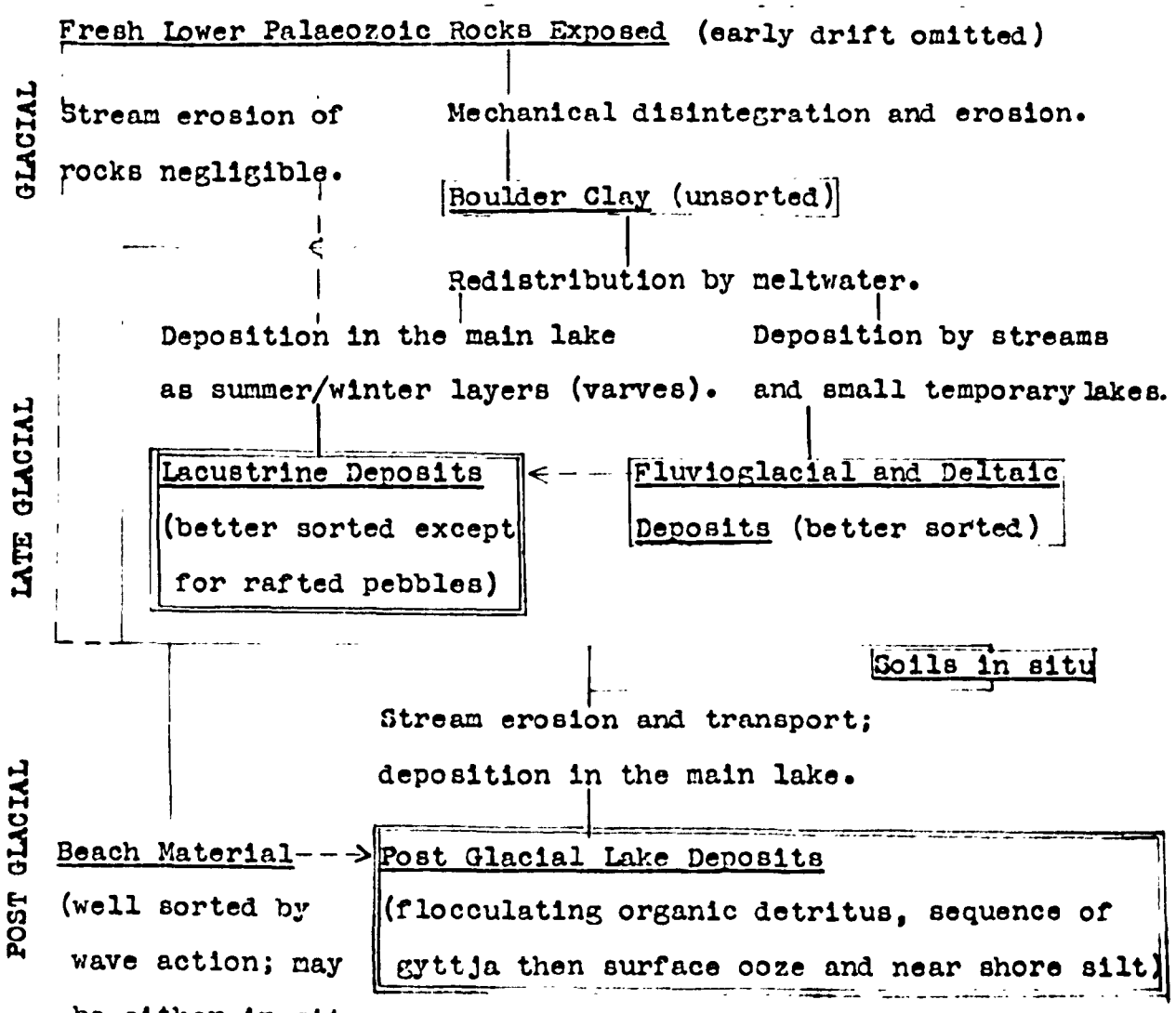
a. Methods for studying grain size in particular, and also mineral composition, of the Post Glacial sediments which are generally unconsolidated, fine grained, organic rich, and floccul--ating. The mechanical methods have had to be modified by a considerable amount for this material; most of the qualitative methods are standard and have been described elsewhere. The validities of the methods used here, and suggested for wider use, were comprehensively tested by a variety of techniques; the results of these tests are presented for examination.

b. The thesis conclusions which concern grain size populat--ions, with special emphasis on silt and clay. These postulate a fundamental division between chemically altered and flocculating hydrated illitic and amorphous clay material and chemically un--altered and non flocculating chloritic and quartzose silt material This division is probably visually distinctive at a size of about 0.020 mm and should have wider application.

c. Interrelationships observed between some of the propert--ies of some of the sediment types may have wider application. Windermere is a confined basin with comparatively well defined and accessible zones of erosion and deposition. The attempt made here to express "significant" relationships between the data from the deposits and the processes involved in their accumulation may be said to place the basin in the category of a non - tectonic stratigraphical model (cp. tectonic models of Sloss, 1962).

Methods Adopted to Achieve Purposes of the Study.

The simplified mechanical flow diagram for mineral matter in the basin is shown in figure 8, it is based entirely on



Present day "drift" in the basin.

Lake material protected from erosion for the present.

N.B. The weathering processes are superimposed on this diagram in figure 117, after all the qualitative analyses had been performed.

Figure 8. Simple Mechanical Flow Diagram of Mineral Matter.

the principles of Late Quaternary geology outlined in the second section of Chapter 1. The movement of sediment particles from their sources to their incorporation in bottom deposits in the lake may be divided into four phases;

a. Weathering at source of rock material, drift, or soil.

b. Erosion and stream transport.

c. Deposition in the lake, temporary at first due to fluctuating water movements.

d. Final burial under later material.

None of these phases was closely studied directly (though siltmeters and other methods were considered for an examination of phases c and d). It is therefore emphasised that the methods adopted for the different aspects of this study are indirect. They involve the sampling of the types of Windermere material, the analysis of the samples (general flow sheet, fig. 9), and finally a statistical and graphical examination of the data before the processes of deposition are finally postulated.

Analyses. (fig. 9)

a. Miscellaneous Analyses. Flocculation, pH, water content, and organic content, are of value in certain aspects.

b. Physical Analyses. Mechanical analyses of both fine and coarse material lead to the classification of sediment types and sedimentary environments, to local variations due to locality and transport media, to the methods finally used, to interrelation--ships between properties, and to grain size populations. Round--ness analyses of the coarser material lead to the abrasive proc--esses in streams and on beaches as well as providing a secondary criterion for the classification of glacial drift clays; these are probably not effective below the zone of effective wave action.

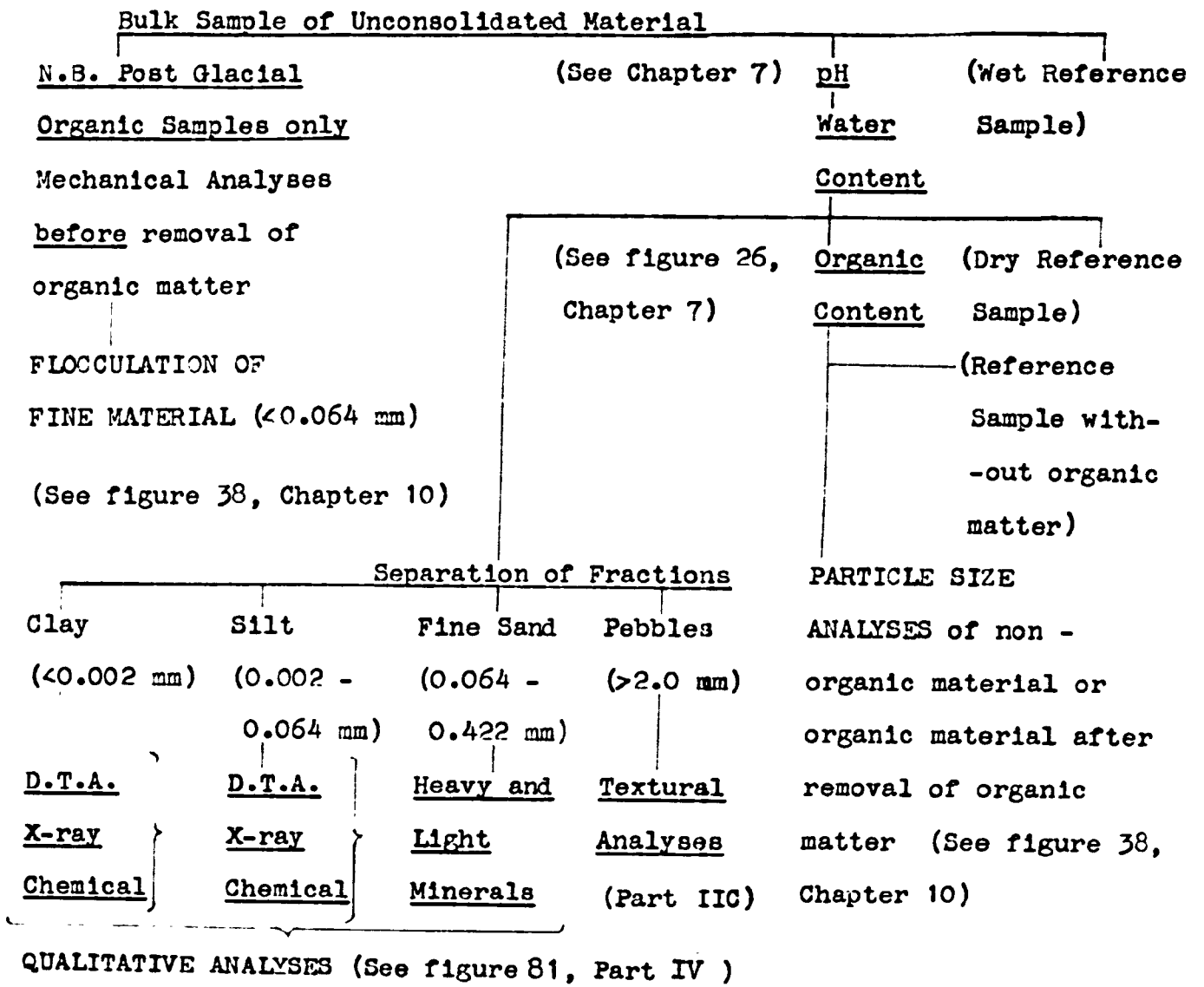


Figure 9. Generalised Flow Sheet of Techniques.

c. Qualitative Analyses. Differential thermal analyses, in particular, and also X-ray and chemical analyses of fine material lead to the alteration processes and to the evolving weathering environments; also to the upper grain size limit of chemically altered clay mineral material; and to the methods used. Neither these fine analyses nor the heavy and light sand mineral analyses were a guide either to the source areas or to the distribution patterns of particles in the lake.

PART II. METHODS.

PART IIa. SAMPLING, CATALOGUING, MATHEMATICAL RELATIONSHIPS, AND MISCELLANEOUS ANALYSES.

Chapter 4. Sampling Procedures.

Determining Localities.

Sextant and Station Pointer.

Sampling localities in a boat on the lake (core and surface samples) were generally positioned with a sextant by taking two separate angles between pairs of three or four landmarks, these are numbered (table 3); the water depth was also taken in each case. These localities were plotted, first onto rough maps with a station pointer, and then, in conjunction with a bathymetric chart of the lake, onto the appropriate trip maps. The angles were generally near to right angles for more accurate locating with the station pointer.

Map.

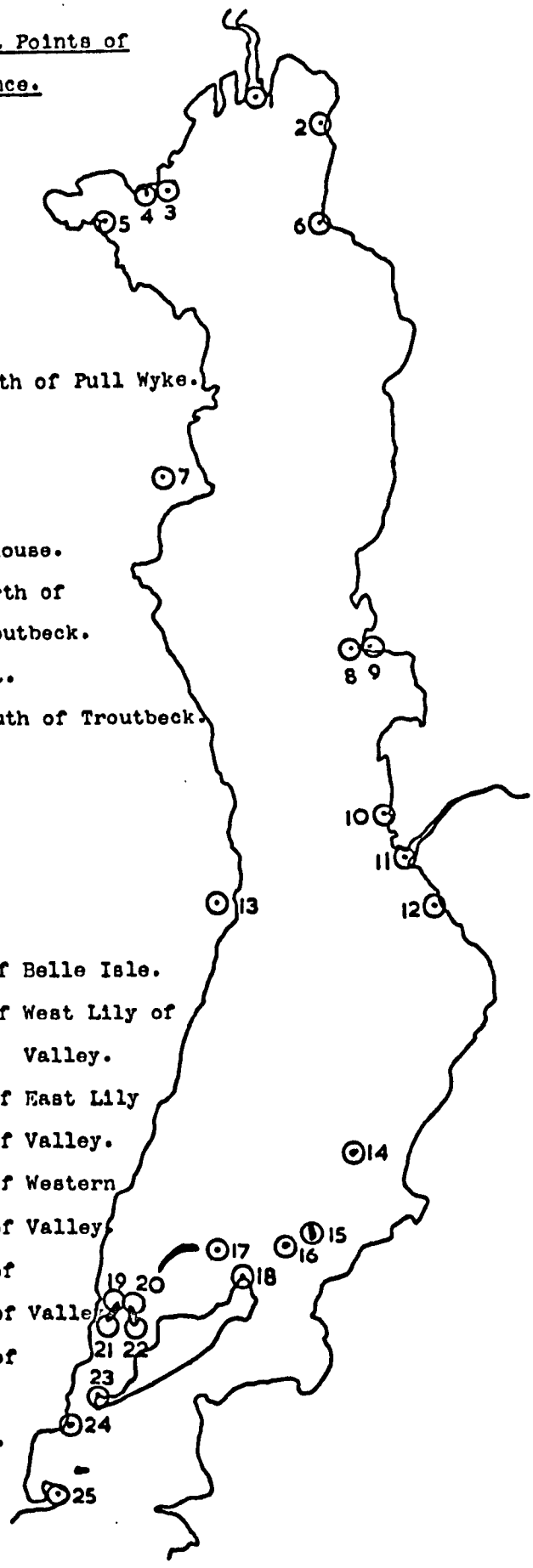
In certain cases localities on the lake could not be determined with the sextant, either because of rain or low visibility. The depth was taken as usual, the position was estimated with a compass, marked onto the rough map and, finally, onto the trip map using the bathymetric chart in the laboratory.

The localities of shoreline, island, and inland samples were estimated and marked onto the rough map in the field.

N.B. Six inch to one mile maps were used throughout.

Table 3. Sextant Points of Reference.

1. Rothay Inlet.
2. Ambleside Pier.
3. Seamew Crag.
4. Brock Crag.
5. Small point North of Pull Wyke.
6. Holme Crag.
7. Wray Castle.
8. Ecclerigg Crag.
9. Ecclerigg Boathouse.
10. Small point North of Troutbeck.
11. Troutbeck Inlet.
12. Small point South of Troutbeck.
13. Belle Grange.
14. Rough Holme.
15. Lady Holme.
16. Hen Holme.
17. Haw's Holme.
18. Northern tip of Belle Isle.
19. Northern tip of West Lily of Valley.
20. Northern tip of East Lily of Valley.
21. Southern tip of Western Lily of Valley.
22. Southern tip of Eastern Lily of Valley.
23. Southern tip of Belle Isle.
24. Coatlap Boint.
25. Ferry House.



A Discussion of the Term "Facies".

The term "facies" is used in a more specialised sense with respect to Post Glacial deposits in Windermere than is usual in geological literature. Here it is defined as "exactly contemp--oraneous deposits of the same sedimentary type". The fact that this is such a short period of geological time gives the contempor--aneity of the deposits special significance. "Exactly contempor--aneous", for surface ooze, means samples taken within a few days of one another; and for gyttja, means samples taken at the same arbitrary chronological level (this is explained below). The more usual meaning of the term is applied with respect to the entire sequences of ooze and gyttja, when contemporaneity is not so impor--tant. The latter is also applied to Late Glacial deposits because exact contemporaneity is not easily assessed.

Ideally, the samples are representative of a "facies" at a locality; during this study, it was inherent that certain factors influencing the identification of "facies" were not known immediat--ly. Three examples of this:

a. It was not immediately realised that the sedimentary properties of the surface ooze varied according to the prevailing climatic and limnological conditions. Thus an ooze sample from a locality in July belongs to one "facies" while a sample from the same locality in December belongs to another "facies". The inference is that it was not possible to identify the "facies" until this was known.

b. Sampling gyttja down a core necessitates the identification of several "facies" at different chronological levels within the gyttja sequence or large facies (see below).

c. The sedimentary origin, and hence the facies, of

certain Late Glacial clays was not possible to determine until a sedimentary analysis had been performed in the laboratory; thus a pebbly and/or sandy clay may have been sampled from the lake shore but it was necessary to know the sorting value of the coarse material before it could be classified as either a boulder clay or a fluvio-glacial clay.

Representative portions of material were sampled, where possible, using the "spot sampling"technique (Krumbein and Pettijohn, 1938, p.13). This involves a number (four here) of small samples of the same "facies" from one locality and combining them before analysis. Errors in specific samples are probably nearly eliminated by this method, though inherent sampling errors are clearly unaffected.

Lake material was sampled on a wide grid (fig. 19, below) though this was made closer off the rivers Troutbeck and Brathay in order to make a more detailed study of the dynamic conditions there. Shoreline samples were generally collected on a wide grid; unusual material was always sampled.

Sampling.

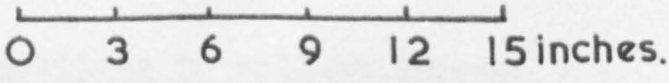
Surface Sampling.

Surface ooze, gyttja lying immediately beneath the ooze, and the pale clay at or near the sediment surface in parts of the shallow "threshold" region were sampled with the F.B.A. Automatic Surface Sampler (fig. 10). The mechanism is set prior to sampling by pulling the valve open and fastening it in this position. When dropped to the lake floor water escapes up the perspex tube and out of the valve at the top. The drop is controlled with the rope, otherwise pressure builds

Figure 10. F.B.A. Automatic Surface Sampler.

(Photograph supplied by F.B.A.)

Shows 9 and 3 lbs weights and 19 inch tube.



up inside the tube and it tends to "skid" sideways. When the sampler falls onto the sediment the sharpened lower edge of the tube is driven into the unconsolidated material to a depth depending on:

a. The resistance offered by the sediment; ooze is soft, clays tend to be hard.

b. The weight of the sampler; this can be adjusted by the number of lead weights attached. 5, 10, 15, 20, 25, 30 lbs were available choices.

c. Length of the tube;three perspex tubes were available, 10 ins, 12 ins and 19 ins long

At the same time the valve mechanism is automatically released so that there is a vacuum at the top of the tube when the sampler is hauled back to the surface. This holds the sediment inside as a short core. The sampler is attached to a rope 70 metres long so that it can be used in all parts of the lake. This rope is marked with linen tags at 5 metre intervals to facilitate the measurement of water depth at any locality. The accurate depth is assessed with a metre rule between tags, making sure the rope is tight.

Surface sampling is done from a small wooden dinghy with an outboard motor.

The sampler sometimes fails to hold material; this is probably due to a semi liquid sludge at the bottom or to a stony, sandy, or hard packed clay bottom.

Expeditions to collect Surface Ooze.

The tube was made to penetrate through the ooze to the material beneath when possible. If this was clay 20, 25, or

30 lbs were needed; if it was gyttja, 10 lbs were generally enough; in these cases the 12 inch tube was used. In places the ooze was deep and the 19 inch tube was needed to penetrate to semi plastic material; in these cases 20 lbs were used. In rare cases even this long tube was insufficient to penetrate right through the ooze. In every case, however, all of the ooze that was brought up in the tube was stored. The operation was repeated four times at each locality, the four "spot samples" thoroughly mixed, and approximately 200 ml of material retained. Where possible the mixing was left until the material was in the laboratory.

It is realised that this method of sampling all the ooze at each locality may lead to inaccurate identification of the "facies" involved; but it is necessary because there is no stratification within the ooze. Instead there is a gradual transition down through the ooze from semi liquid dark brown material to semi plastic black material which generally overlies gyttja with a sharp boundary. It is probable that the black material has attained mechanical stability. If so, this stable material will have the affect of "diluting" the more recent deposits (the true "facies") in any sample and is thus a cause of a sampling error. This was realised but it was decided to adhere to this method because of the impossibility of demarc-ating stable and unstable material.

Expeditions to collect Gyttja.

It was necessary to penetrate the ooze overlying the gyttja; the conditions for this are mentioned above. Three inches of gyttja immediately below the junction with ooze was

sampled and any further material discarded. Four "spot samples" were taken at each locality and about 200 ml retained after mixing in the laboratory.

Expeditions to collect Clay Material.

Again it was necessary to penetrate the material that was overlying the clay though in many cases this amounted to no more than a veneer of semi-liquid ooze drifting on the hard surface of the clay in the shallow "threshold" region. The problem of penetrating the clay sufficiently has been mentioned, 30 lbs were sometimes needed. At localities where the clay was uniform, the top three inches were sampled and the "spot samples" mixed in the laboratory. At some localities, however, the clay was distinctly "rusty" near the top, grading down into smoother material. Here, three inches of each type was sampled and kept separate.

Hypothetical surface samples are shown in figure 11.

Material sampled in the surface sampler was stored in polythene screw-cap bottles of 50, 100, and 200 ml capacity.

The sampler was thoroughly washed in the lake before use.

When the F.B.A. Sampler was not available, the Jenkin Surface Sampler was used instead (fig. 12).

The short cores brought up at each locality were measured and described (Field Notes, Appendix No. 2).

Shoreline Sampling.

Beach Material and Near Shore Silts.

The beaches around the lake are generally small and crescentic; they are cut into earlier material by wave-action.

Figure 11. Field Examination of three Surface Samples.

(N.B. Hypothetical)

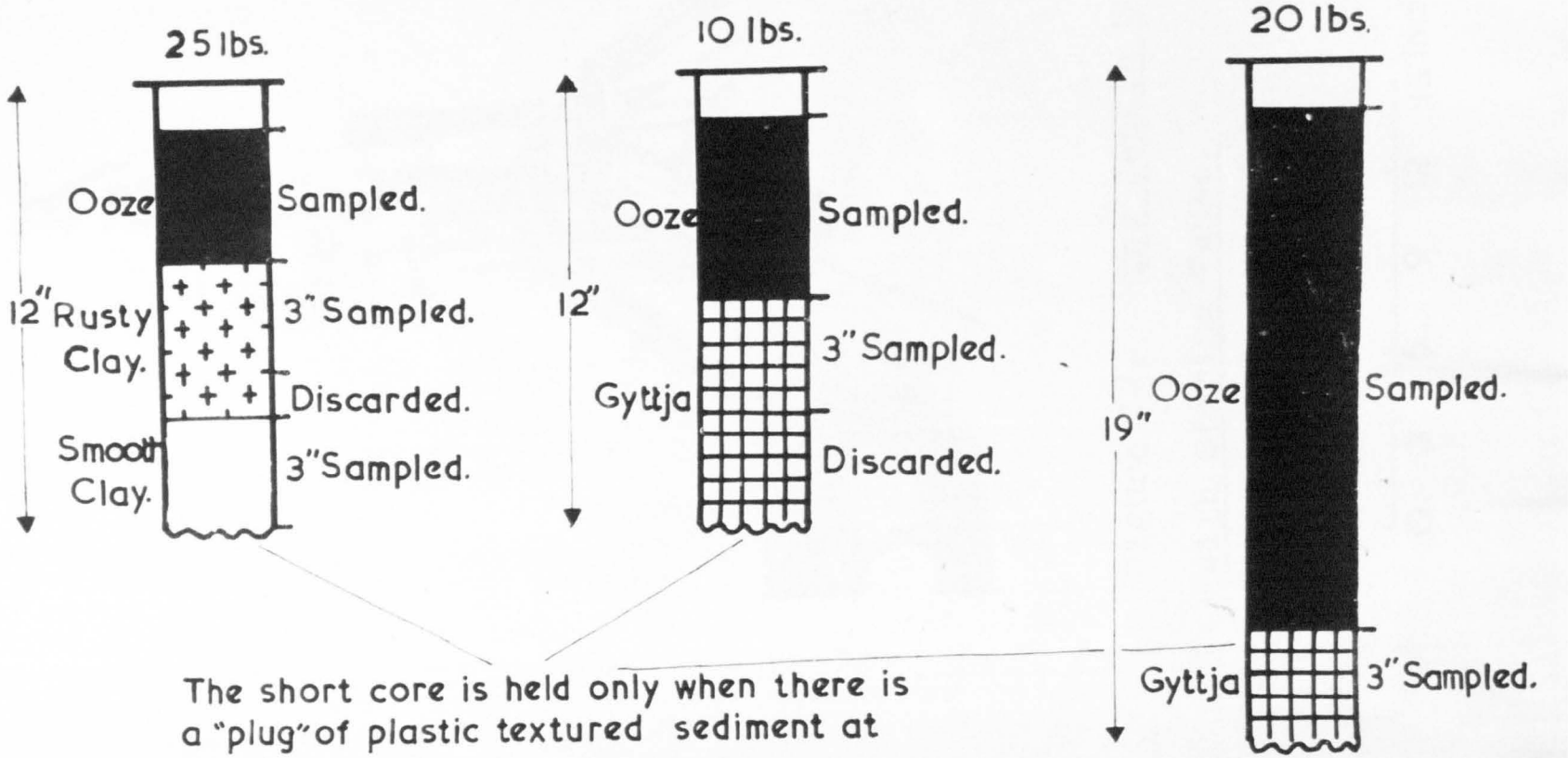


Figure 12. The Jenkin Surface Sampler with Storing Tubes.

(Photograph supplied by F.B.A.)

0 3 6 9 12 15 inches.

They are very varied with respect to the particle size of the beach material. Some are composed of boulders (under Claife Heights on the Western side of the North Basin), some of moderately fine sand only (Cockshott Point), and others of all sizes. However, it was generally found that a comparatively well sorted (as observed in the field) "shoestring deposit" at the water's edge stood out from the rest of the beach. Sometimes there were several of these, parallel to one another on one beach (fig. 13 a, b, c, and d) grading from the coarsest at the water's edge through to finer material further back. The deposit furthest from the water's edge was sometimes composed of coarse vegetable detritus (fig. 14a). Unless otherwise stated, four small "spot samples" are taken from the beach material at the water's edge, from points up to two feet apart along its length, and combined to make a composite sample to fill a 50 ml polythene screw-cap bottle.

Near shore silts with organic detritus (fig. 14b) occur just off-shore in sheltered water about a metre deep. They were sampled and stored in 50 ml polythene bottles before mixing in the laboratory.

Positions were determined from the map and the localities described in the field notes (Appendix No. 2).

Late Glacial Clays.

These are found either underneath beach material or as part of the wave-cut section behind the beaches on the lake shore and on the islands. It has been mentioned that identification of facies cannot always be made in the field;

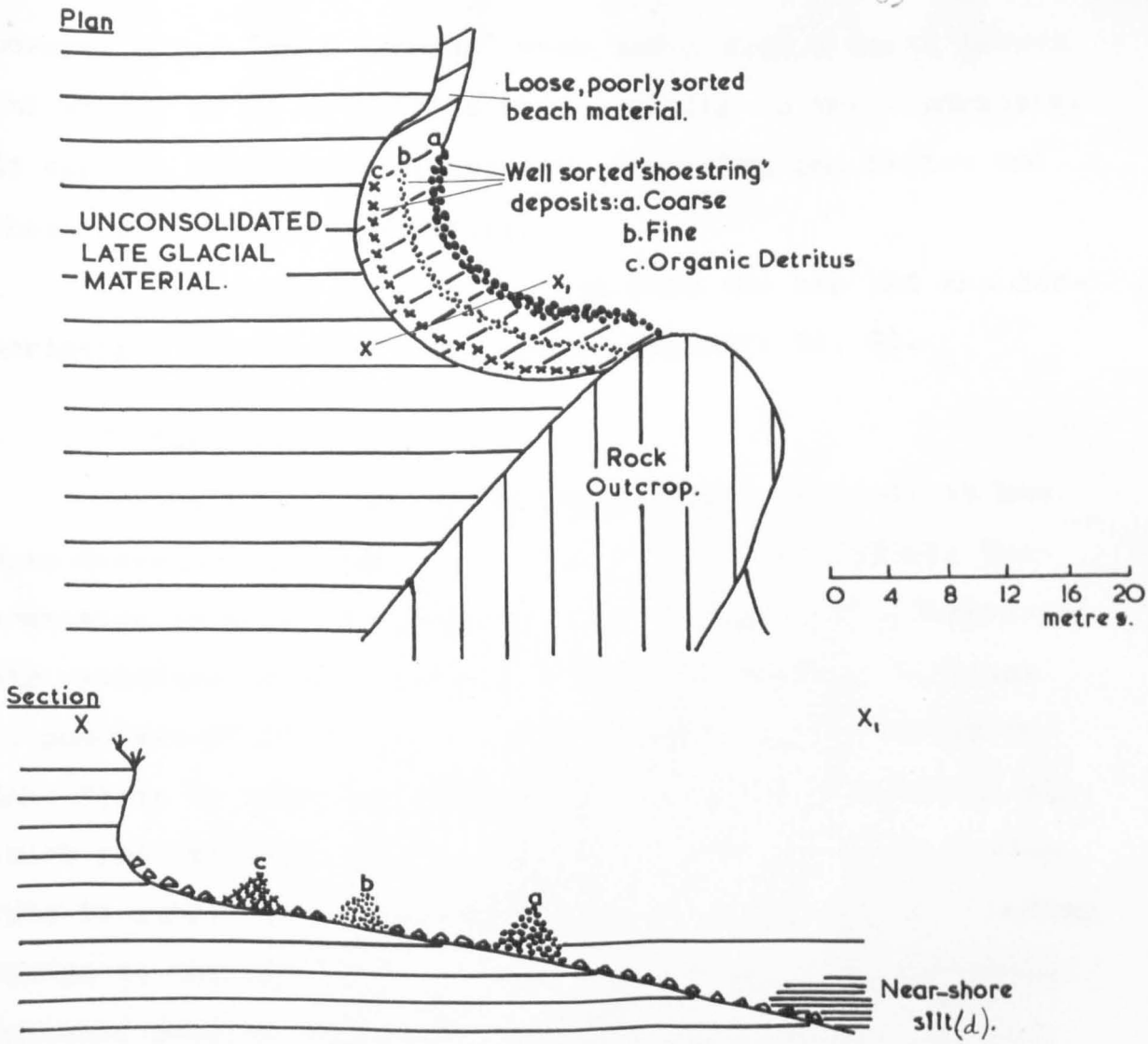
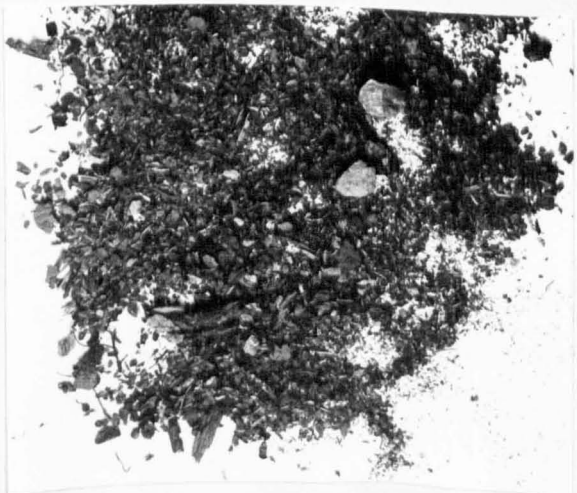


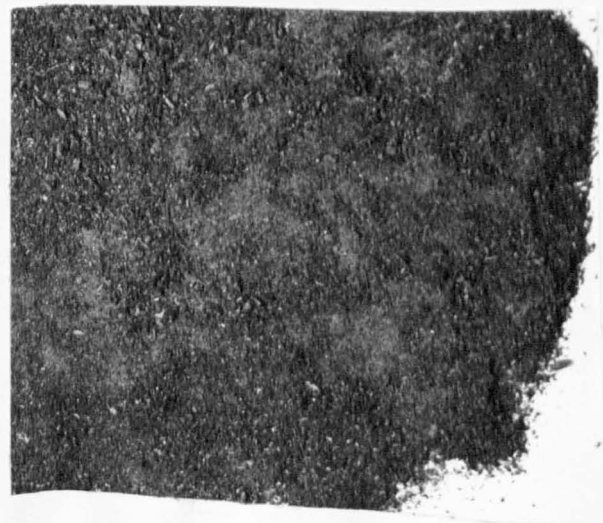
Figure 13. Present Day Deposits on a Hypothetical Crescentic Beach.

Figure 14. Photographs of Beach Deposits. (x1)

a. Organic Detritus (c above). Also two pebbles.



b. Near Shore Silt (d above). Discrete organic and mineral grains.



however four "spot samples" were taken with a small trowel and stored in 50 ml bottles before mixing in the laboratory. At certain localities there were more than one facies and these were sampled separately.

Positions were determined from the map and the descriptions are in the field notes (Appendix No. 2).

Core Sampling.

The F.B.A. Mackereth Core Sampler is used; it has been described by Mackereth (1958) and Smith (1959a). The operation is shown diagrammatically in figure 15. Compressed air cylinders in the anchored dinghy are used as follows: To pump water out of the drum to "anchor" it firmly on the lake floor by hydrostatic pressure (I and II). Then the air lines are switched over in the dinghy and the inner coring tube is pumped down into the sediment by means of the moving piston at the top (III). The air pressure is automatically switched over to refill the drum and extract it from the lake floor (IV). The core in the inner tube is held by the vacuum at the top. The drum tends to "explode" to the water surface so this is minimised by a valve which allows air out of the drum when it is off the lake floor (V); and also by a gate attached to the outer tube which swings open when moving upwards. The corer is floated ashore, the inner tube is pumped back inside the outer tube leaving the core to be stored in wooden trays, wrapped in polythene, firmly taped, and labelled. The apparatus takes a core of maximum length 20 feet and diameter 1¾ inches; the wooden trays are 5 to 6 feet long so four are generally needed for one core. The corer

Figure 15. Operation of the Corer. (Mainly taken from Smith, 1959a)

cannot be used in water less than about 15 metres deep.

Sampling Along a Core.

Ideally the samples taken down one core are correlated chronologically with those taken along the length of every other core in order to examine sedimentary features in the lake at several definate intervals. It was not practicable to use Pennington's pollen zones (1947a) because they are comparatively broad in terms of depth of sediment, whereas samples only six inches long were taken here. The methods used for correlating the samples are given below.

No cores were taken from water shallower than 15 metres; this eliminated correlationdifficulties due to unconformities in shallow water (fig. 7d). This is also the reason for not finding clay bands opposite stream mouths in Zone VII. In all the cores taken in this work it is assumed that there are no unconformities in the Post Glacial sequence of lake sediments.

Gyttja. The depth of gyttja from the the top of the core was measured to the top of the Late Glacial material, if included at the base, and/or to the topmost clay band of the transitional sequence. Both these horizons are well marked statigraphic boundaries. It then had to be assumed that the rates of sediment accumulation had been uniform through-out the periods of deposition of the transitional sequence and the gyttja respectively. These two measured depths in the individual cores were therefore divided into specified ratios. Thus an approach to contemporaneity of samples was made. The cores were sampled on this principle as follows:

a. Late Glacial material present at the base: one gyttja sample (D - level) was taken halfway between this and the topmost clay band, a second (C - level) immediately above the clay band, a third (A - level) at the top of the core, and a fourth halfway between the A and C levels (B - level).

b. Late Glacial not present: A, B, and C levels only.

c. Two cores from very close localities (C7 and C8, Chapter 5) were sampled at closer intervals as a check on the method. From these cores two further samples (e and f) between A and B levels, two (g and h) between B and C levels, and one (i) between C and D levels were taken.

d. Features of interest, such as sandy, "coky", or clay layers within the gyttja were taken from certain core samples.

Approximately 200 ml of wet gyttja was taken in each case, the base of this six inch column being at the calculated sampling level. The gyttja levels (9) each represent a different "facies"; surface sampled gyttja is treated as A - level "facies".

Theoretical Sampling Considerations. It is emphasised that there were two choices of sampling the visually nearly homogeneous gyttja facies (term used in its normal sense) down the cores. It may have been useful to take several end to end "scrape" samples, in effect a long thin slivver of material divided into samples at specific intervals. These would have tended to eliminate the minor stratigraphic discrepancies due to early Post Glacial localised variations to which the present method is prone. On the other hand surface ooze, a closely compared facies, is "spot sampled" from short cores and the present method has more in common with this.

Late Glacial Lacustrine Material. This varies down the cores and from locality to locality; only rarely were core sequences

tentatively correlated. However it was more important that the clays, silts, sands, and pebbly layers were examined as general facies. The quantity of material taken depended on circumstances; 200 ml was the maximum.

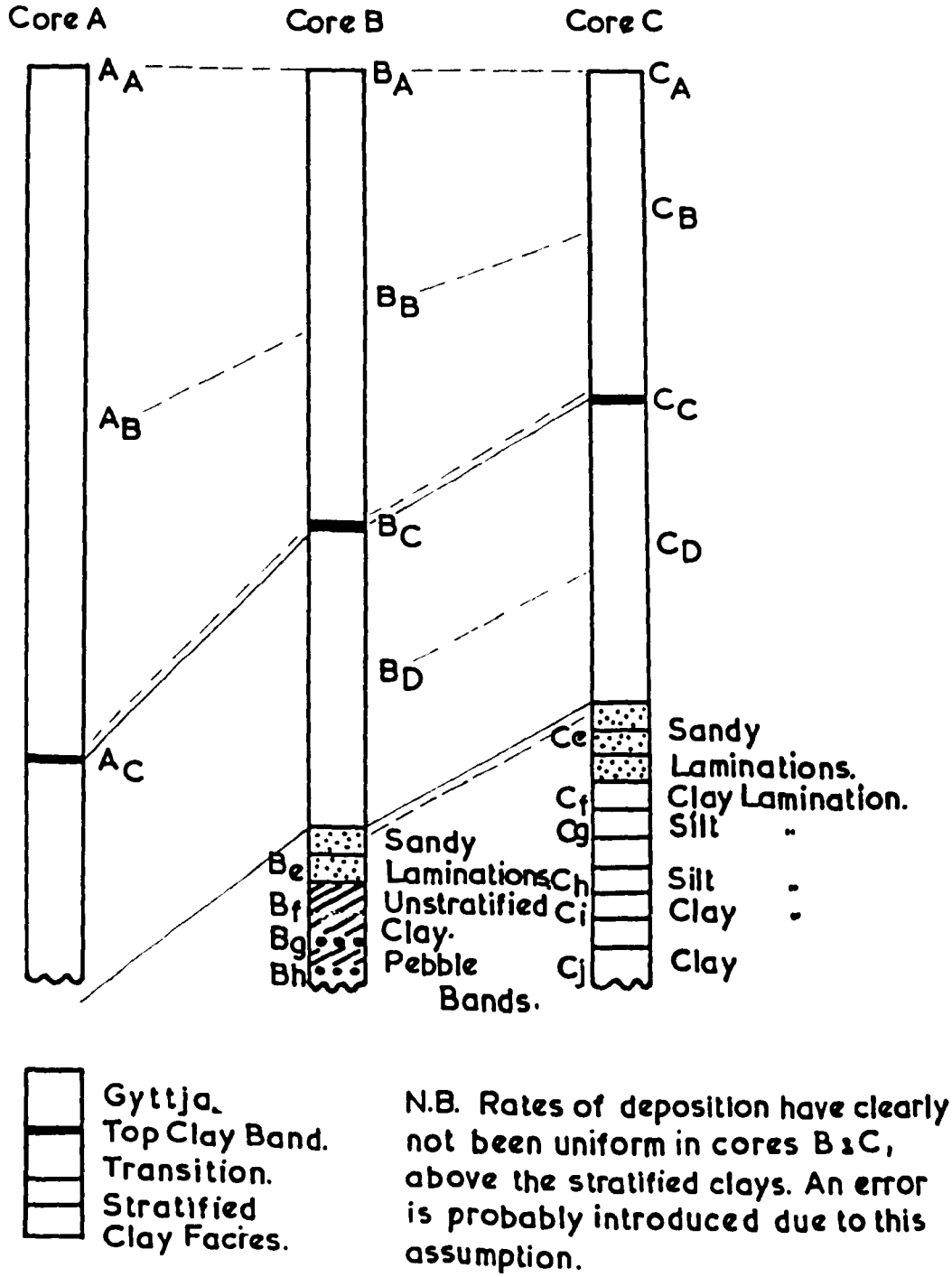
The sampling techniques are shown on the hypo--thetical cores in figure 16.

N.B. Each core was scraped with a knife after unwrapping in the laboratory. This clarified structures and boundaries and facilitated measurement and sampling. Figure 17 shows how the cores were described. They are all figured in Appendix No. 2.

Samples from the Catchment Area.

Small portions of certain rock, soil, and boulder clay samples collected by Pink (personal communication) from the catchment area of Windermere were used here exclusively for qualitative analyses. They were chosen to include a representative cross section of various types in the area. All these samples were taken from streams or exposed sections in the watershed areas of the rivers Stock Ghyll, Hol Beck and Troutbeck. The localities were positioned on the map but they are not described here. A generalised diagram of the soil/rock succession is shown in figure 18.

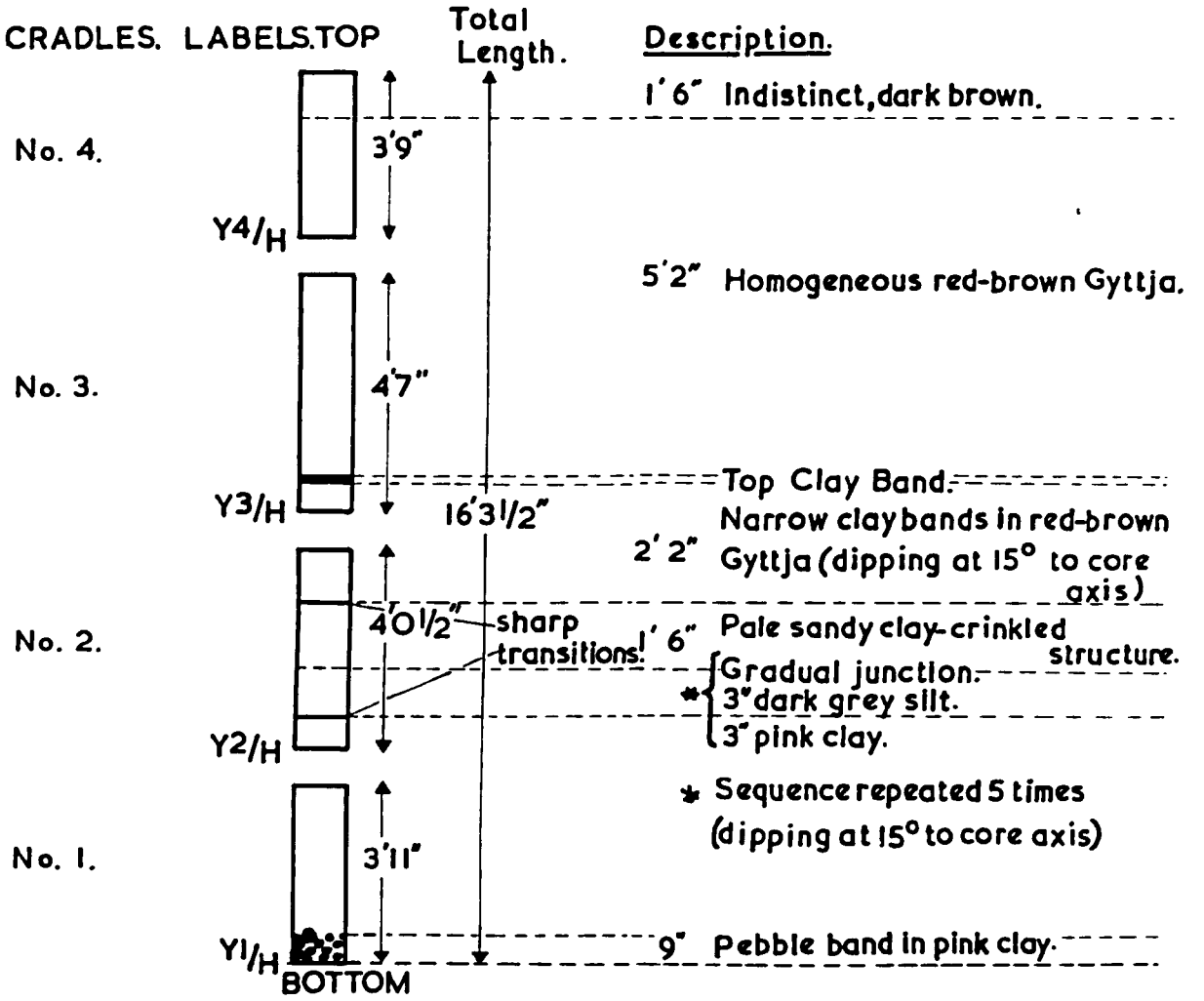
Figure 16. Chronological Correlation between Samples in three Hypothetical Cores (Nos. A, B, C.).



N.B. Rates of deposition have clearly not been uniform in cores B & C, above the stratified clays. An error is probably introduced due to this assumption.

Figure 17. Laboratory Examination of a Hypothetical Core.

("No. Y")



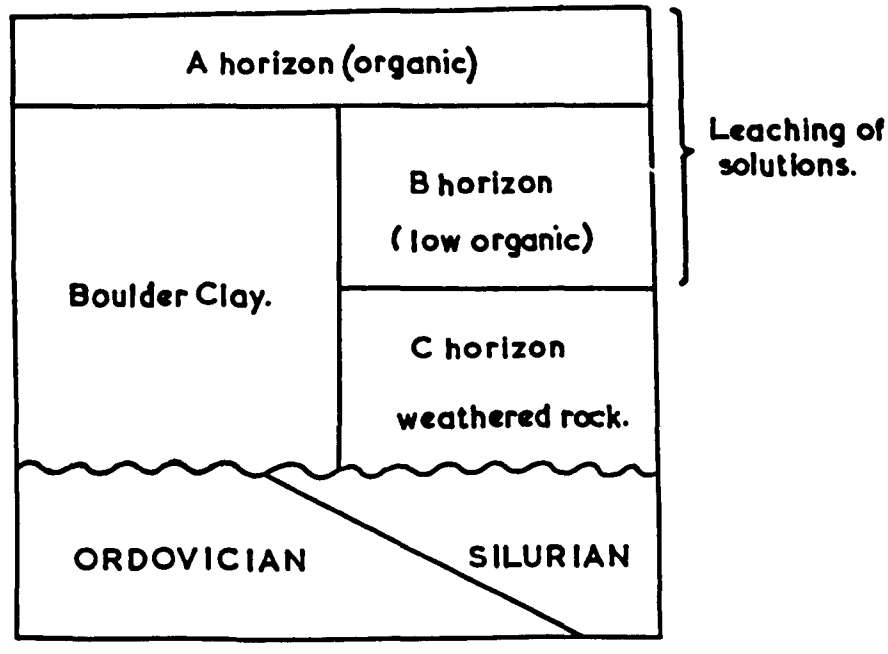


Figure 18. Simplified and Generalised Cross-Section of the Rock - Soil Relationship in the Catchment Area.

Chapter 5. Field Notes and Cataloguing Procedures.

Field Notes.

Notes were made about each locality and each sample. It was necessary to catalogue these notes (along with any further information obtained from a laboratory examination) listing: Sample No., Locality No., position, water depth and a description of the material at the locality.

Six visits were made to Windermere during this study and to each one of these is assigned a "Trip No." (1 to 6). The date of sampling and the collectors' initials are recorded. Each sampling locality is given a "Field Locality No.": surface samples S1, S2, S3; shoreline samples B1, B2, B3; and core samples C1, C2, C3; each starting at 1 for each trip. If positioned by sextant the readings are noted. An example of the field notes is shown in table 4; they are all catalogued in Appendix No. 2.

Labelling Samples.

Surface and Shoreline Samples.

The polythene bottles, in which the unconsolidated material was stored, were numbered in a continuous series from 1 to 250 (when available, there were only 80 of these altogether). In the field no effort is made to keep them in numerical order. The bottle nos. are tabulated in the appropriate column opposite the corresponding S or B Locality Nos.

Core Samples.

The cores were numbered in a continuous series in

Table 4. Hypothetical Example of Field Notes.

Trip No. 3; Date: 2:3:'61. Collectors: P.W.H., F.P., B.W.

Type of Sampling.	Field Locality No.	Position.	Depth.	Numbers.
a. Surface Sampling Locality. (measured and described.)	S4.	20-30: 22° 41'. 30- 40: 81° 17'.	17M.	Ooze: 147,152, 161. Clay: 157,158, 160. Gyttja: 148,149, 150,162.
b. Beach Sampling Locality. (measured and described.)	B12.	See map, Brathay Delta.	--	Beach Material: 137. Silt: 131. Clay: 140.
c. Core Sampling Locality.	C2.	1-20: 49° 02'. 20-35: 43° 51'.	27M.	Core No. 7.

order of extraction. Thus the five cores collected on the first visit were numbered from 1 to 5 and the two on the second visit were numbered 6 and 7. These core numbers are tabulated opposite the appropriate C locality nos. The wooden core section cradles were labelled with Indian Ink as follows: the bottom cradle is No. 1 for each core and the top is No. 4; each cradle is labelled at the bottom end for easy reference (fig. 17).

The cores were not normally described in the field (unless a feature may be obscured during storage). They were measured and described when unwrapped in the laboratory.

Cataloguing Procedure.

Different symbols were used on the trip maps for S, C, and B locality nos. After all the samples had been taken these localities were plotted onto three separate "Comprehensive Maps" respectively; these are bathymetric charts of the lake (fig. 19 a,b, and c). Sampling localities in the watershed area are shown on figure 19d. The points on these maps (N.B. not 19d) were assigned with the ultimate "Catalogue Locality Nos." (S1, S2, S3; C1, C2, C3; B1, B2, B3) which are mentioned in the thesis unless otherwise stated. Thus each sampling locality has a field locality/trip no. and a final catalogue no.

When the samples were prepared for examination in the laboratory, they were each assigned with a "Data Sheet No." in order of analysis used for tabulating the data obtained from its examination. These sheet nos. were tabulated opposite the corresponding field locality and trip nos. and in the

appropriate facies column. In the core samples there were several data sheet nos. opposite each locality no. In the case of the surface and shoreline samples there may have been one sheet no. opposite several "spot sample" nos. (taken from one locality). Also there may have been more than one sheet no. opposite each locality no. (if there were more than one facies sampled there).

After all the samples had been analysed the sheet nos. were assigned with the ultimate "Catalogue Sample Nos.". These are referred to in the thesis unless otherwise stated; they are tabulated opposite their catalogue locality nos. in table 5. Both catalogue locality and sample nos. are generally numbered from the north. In cases where two types of sampling locality are involved in the collection one facies (A - level gyttja, fluvioglacial sediments) the two locality series are each numbered from the north consecutively. In cases where there is more than one sample of the same facies at the same locality (Late Glacial lacustrine facies in the cores), they are numbered in an appropriate order; the cores, for example, are numbered downwards. The rock and soil samples from the watershed area are catalogued from the north as well as possible. The different rock and soil types are not distinguished in table 5. (N.B. These are not given locality nos. and are found on the map, figure 19d, by sample nos. alone.)

Field Notes/Catalogue Nos. Cross References.

Catalogue sample nos. are listed with catalogue locality nos. in table 5 and the localities are found on figure 19. The corresponding field locality and trip nos. are

also listed in table 5. The descriptions of the localities and diagrams of the cores can be referred to in Appendix No. 2 along with further information about each locality, such as details of positioning, "spot sample" nos., and collectors' initials (table 1), by using the appropriate field locality and trip nos. found in table 5. The data sheet nos. are also available, as a check, in both tables 5 and 1.

List of Facies in Table 5 Described.

Post Glacial Material (PG...).

Present Day Deposits.

Surface Ooze (PGa). Dark brown organic semi liquid material at the sediment/water interface grading down into dark grey semi plastic material.

PGa1. Windermere, January 1961.

PGa2. Windermere, April - May 1961.

PGa3. Windermere, August 1962; after heavy floods.

PGa4. Grasmere, August 1962; (before floods).

PGa5. Rydal Water, August 1962; (before floods).

PGa6. Elter Water, August 1962; (before floods).

Near Shore Silt (PGb). Light grey mixtures of fine but discrete mineral and rock particles and discrete (not flocc--ulating) organic debris; June 1962 only.

Beach Material (PGc). Sand at water's edge; June 1962 only.

Early Post Glacial Deposits.

Gyttja (PGd). Reddish semi plastic to plastic organic mud beneath surface ooze.

PGd1. A - level; top of cores and surface samples.

PGd2. B - level; halfway between A and C levels.

PGd3. C - level; above top clay band.

PGd4. D - level; halfway between C and top of Late Glacial clays.

PGd5. e - level; between A and B levels, cores 10 and 11.

PGd6. f - level; between A and B levels, cores 10 and 11.

PGd7. g - level; between B and C levels, cores 10 and 11.

PGd8. h - level; between B and C levels, cores 10 and 11.

PGd9. i - level; between C and D levels, cores 10 and 11.

Sandy Layers (PGe). Thin layers of light grey, friable, and almost non organic sand within the gyttja sequence in cores 9 and 13.

Black "Ooze" Layers (PGf). These are about 20 cms thick and grade up and down into reddish gyttja. They occur about 50 cms below the top in many of the cores. Cores 13 and 15 exhibit peculiar large "coky" fragments within these layers, which are examined.

Clay Bands (PGg). Pink plastic clay. Thick topmost clay bands in cores 9 and 12 are examined. One further clay band, near the base of the transitional facies in core 11, is examined; this latter is very thick and may be a Late Glacial deposit which is found in its present position in the core due to slumping and sliding over its present base plane.

Late Glacial Material (LG...).

Lacustrine Deposits (LGa). Non-organic, varied; found below gyttja in cores from water deeper than 15 metres.

LGa1. Clay. Pale pink plastic clay, collected as laminations where possible. These may be up to 10 cms thick or very thin varves. In the latter case it was not possible to isolate the

clay laminations from the silt. This category includes the pink clay found in association with pebbles at certain levels in some of the cores; the fine material is separated from the pebbles by sieving and is examined as a lacustrine clay.

LGa2. Silt. Dark grey slightly friable, slightly plastic; like clay the silt was collected as laminations where possible. This category includes the grey silt found in association with pebbles in core 17.

LGa3. Sand. Pale grey, micaceous, and friable sand collected as laminations where possible.

LGa4. Pebbles. These are layers in clay or silt containing a proportion of material larger than 2.0 mm. The pebbles are examined as a separate category.

Fluvio-glacial Deposits (LGb). Shoreline or shallow water surface samples.

LGb1. Clay. Either with or without sand and gravel incorporated. If the latter is present it has a sorting value lower than 3.0 and is thus arbitrarily distinguished from boulder clay in this work.

LGb1(i). "Rusty" Clay: Found at certain localities at the top of a shallow water surface sample short core. The colour and the clayey texture are uneven and much of the material is rusty coloured.

LGb1(ii). Smooth Clay: Underneath "rusty" clays in the corresponding short cores; also shoreline samples. The colour and the plastic clayey texture are even except for sand and gravel incorporated in the clay.

LGb2. Sand. One loose sand and one semi consolidated rusty

coloured "sandstone" were collected.

Deltaic Deposits (LGc). These may be of approximately the same age as lacustrine and fluvio-glacial deposits (above) but the special sequences of strata on the flat lying areas near the mouths of the rivers Troutbeck and Brathay suggest that an altogether different set of conditions prevailed during their deposition. Dark grey slightly organic silt with some pebble layers is found sharply overlying pale clayey material (for detailed sections, see figure 1 d, insets 2 and 3.).

LGc1. Clay.

LGc2. Silt.

Boulder Clay (LGd). Shoreline clayey samples with sand and gravel giving a sorting value of greater than 3.0 are arbitrarily distinguished from fluvioglacial clays. in this work.

Soils.

Rocks.

N.B. A full "genetic" classification of sediment types and sedimentary environments appears in Chapter 17, Part IIC.

Also some geomorphological observations were made dur--ing some of the sampling expeditions. These are not of first importance but they are tentatively used later for correlation purposes. These observations are not listed together but they are referred to where appropriate in the thesis; see particular--ly figure 4.

Table 5. List of Samples. (Localities on figure 19)

Present Day Deposits

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
PGa1 Surface Ooze, Windermere; Jan. 1961.	1	S1	62	S8	1
	2	S2	61	S5	1
	3	S3	60	S7	1
	4	S30	66	S13	1
	5	S32	65	S9	1
	6	S37	63	S16	1
	7	S38	64	S20	1
	8	S40	59	S15	1
PGa2 Surface Ooze, Windermere; April - May 1961.	9	C1	13	C1	2
	10	C2	55	C2	2
	11	S11	8	S6	2
	12	S14	9	S4	2
	13	S15	5	S5	2
	14	S18	4	S7	2
	15	S21	3	S8	2
	16	S22	1	S2	2
	17	S25	12	S1	2
PGa3	18	S4	105	S1	5
	19	S5	106	S2	5

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
PGa3 Surface Ooze, Windermere; Aug. 1962. N.B. After heavy floods	20	S6	107	S3	5
	21	S7	108	S4	5
	22	S8	109	S5	5
	23	S9	110	S6	5
	24	S10	111	S7	5
	25	S16	112	S9	5
	26	S17	113	S10	5
	27	S19	114	S11	5
	28	S20	115	S12	5
	29	S23	116	S13	5
PGa4 Grasmere	30	S42	96	S14	5
	31	S43	97	S15	5
	32	S44	98	S16	5
PGa5 Rydal Water	33	S45	99	S17	5
	34	S46	100	S18	5
	35	S47	101	S19	5
PGa6 Elter Water	36	S48	102	S19	5
	37	S49	103	S20	5
	38	S50	104	S21	5

Table 5. List of Samples. (Localities on figure 19)

Present Day Deposits

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
PGb Near-Shore Silt.	39	B25	76	B6	4
	40	B26	75	B5	4
	41	B32	72	B3	4
PGc Beach Material.	42	B1	95	B36	4
	43	B4	94	B35	4
	44	B5	91	B30	4
	45	B6	92	B31	4
	46	B7	93	B32	4
	47	B9	78	B12	4
	48	B11	90	B29	4
	49	B12	89	B28	4
	50	B14	88	B26	4
	51	B16	77	B10	4
	52	B17	86	B22	4
	53	B19	87	B24	4
	54	B31	73	B4	4
	55	B31	74	B4	4
	56	B34	71a	B1	4
	57	B34	71b	B1	4

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
PGc Beach Material.	58	B34	71c	B1	4
	59	B35	85	B21	4
	60	B36	84	B20	4
	61	B37	83	B19	4
	62	B38	82	B18	4
	63	B39	81	B17	4
	64	B41	80	B15	4
	65	B42	79	B14	4

Table 5. List of Samples. (Localities on figure 19)

Early Post Glacial Deposits

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
PGd1	66	C1	23	C1	2
A-Level	67	C2	26	C2	2
Gyttja;	68	C3	37	C1	3
Surface	69	C4	41	C2	3
Samples	70	C5	194	C1	6
and Top	71	C6	198	C2	6
of Cores.	72	C7	202	C3	6
	73	C8	206	C4	6
	74	C9	210	C5	6
	75	C10	28	C3	2
	76	C11	57	C4	2
	77	C12	58	C5	2
	78	C13	214	C6	6
	79	C15	217	C8	6
	80	C17	221	C10	6
	81	S11	7	S6	2
	82	S18	6	S7	2
	83	S21	2	S8	2
	84	S22	11	S2	2

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
PGd1	85	S24	143	S1	6
	86	S25	10	S1	2
	87	S41	144	S2	6
PGd2	88	C1	24	C1	2
B-Level	89	C2	27	C2	2
Gyttja;	90	C3	38	C1	3
2nd level	91	C4	42	C2	3
in Cores.	92	C5	195	C1	6
	93	C6	199	C2	6
	94	C7	203	C3	6
	95	C8	207	C4	6
	96	C9	211	C5	6
	97	C10	29	C3	2
	98	C11	31	C4	2
	99	C12	34	C5	2
	100	C13	215	C6	6
	101	C15	218	C8	6
	102	C17	222	C10	6

Table 5. List of Samples. (Localities on figure 19)

Early Post Glacial Deposits

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
PGd3 C-Level Gyttja; 3rd level in Cores.	103	C1	25	C1	2
	104	C3	39	C1	3
	105	C4	43	C2	3
	106	C5	196	C1	6
	107	C6	200	C2	6
	108	C7	204	C3	6
	109	C8	208	C4	6
	110	C9	212	C5	6
	111	C10	30	C3	2
	112	C11	32	C4	2
	113	C12	35	C5	2
	114	C13	216	C6	6
	115	C15	219	C8	6
	116	C17	223	C10	6
PGd4 D-Level Gyttja; 4th level in Cores.	117	C3	40	C1	3
	118	C5	197	C1	6
	119	C6	201	C2	6
	120	C7	205	C3	6
	121	C8	209	C4	6
PGd4	122	C9	213	C5	6
	123	C11	33	C4	2
	124	C12	36	C5	2
	125	C15	220	C8	6
	126	C17	224	C10	6
PGd5 e-Level	127	C7	225	C3	6
	128	C8	230	C4	6
PGd6 f-Level	129	C7	226	C3	6
	130	C8	231	C4	6
PGd7 g-Level	131	C7	227	C3	6
	132	C8	232	C4	6
PGd8 h-Level	133	C7	228	C3	6
	134	C8	233	C4	6
PGd9 g-Level	135	C7	229	C3	6
	136	C8	234	C4	6

Special check levels in Gyttja; Cores 10, 11.

Table 5. List of Samples. (Localities on figure 19)

Early Post Glacial Deposits

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
PGe Sandy layers in Gyttja.	137	C6	260	C2	6
	138	C13	236	C6	6
	139	C13	237	C6	6
PGf Ooze layers in Gyttja, with "coky" fragments.	140	C13	235	C6	6
	141	C15	238	C8	6
PGg Clay Bands in Gyttja. (*Top)	142*	C6	259	C2	6
	143	C8	256	C4	6
	144*	C9	261	C5	6

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.

Table 5. List of Samples. (Localities on figure 19)

Late Glacial Deposits

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
LGa1	145*	C3	51	C1	3
Lacustrine	146*	C3	52	C1	3
Pink Clay;	147	C3	53	C1	3
varves	148*	C3	54	C1	3
collected	149	C5	239	C1	6
where	150	C6	240	C2	6
discernible	151	C7	262	C3	6
	152	C7	263	C3	6
*Fine	153	C8	257	C4	6
Fractions	154*	C8	258	C4	6
of Pebbly	155	C9	241	C5	6
Layers.	156**	C9	242	C5	6
	157	C12	46	C5	2
**Contains	158	C12	48	C5	2
a high	159	C12	50	C5	2
proportion	160	C15	244	C8	6
of	161*	C15	246	C8	6
Vivianite.	162	C15	247	C8	6
	163	C15	249	C8	6
LGa1	164	C15	252	C8	6
	165	C17	255	C10	6
LGa2	166	C9	243	C5	6
Lacustrine	167	C12	47	C5	2
Dark Grey	168	C12	49	C5	2
Silt;	169	C15	245	C8	6
varves	170	C15	248	C8	6
collected	171	C15	251	C8	6
where	172*	C17	253	C10	6
discernible.	173	C17	254	C10	6
LGa3	174	C7	264	C3	6
Lacustrine	175	C11	56	C4	2
Light Grey	176	C11	44	C4	2
Sand	177	C12	45	C5	2
Layers.	178	C15	250	C8	6
LGa4	179	C3	51	C1	3
Lacustrine	180	C3	52	C1	3
Pebbly	181	C3	54	C1	3
Layers.	182	C8	258	C4	6

Table 5. List of Samples. (Localities on figure 19)

Late Glacial Deposits

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
LGa4	183	C15	246	C8	6
	184	C17	253	C10	6
LGb1i Fluvio - Glacial "Rusty"Clay; surface samples.	185	S26	18	S4	3
	186	S27	16	S3	3
	187	S29	15	S2	3
	188	S33	20	S6	3
	189	S35	22	S8	3
	190	S39	68	S11	1
LGb1ii Fluvio - Glacial. "Smooth"Clay; surface and shoreline samples.	191	B8	124	B13	4
	192	B16	121	B10	4
	193	B20	142	B42	4
	194	B21	137	B37	4
	195	B22	138	B38	4
	196	B27	139	B39	4
	197	B28	140	B40	4
	198	B29	141	B41	4
	199	B37	127	B19	4
	200	B39	126	B17	4

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
LGb1ii	201	B40	125	B16	4
	202	S27	17	S3	3
	203	S28	14	S1	3
	204	S30	67	S13	1
	205	S31	19	S5	3
	206	S33	21	S6	3
	207	S36	69	S17	1
	208	S37	70	S16	1
LGb2 "Sand".	209	B10	122	B11	4
	210	B37	128	B19	4
LGc1 Deltaic Clay.	211	B4	135	B35	4
	212	B12	131	B28	4
LGc2 Deltaic Silt.	213	B2	134	B34	4
	214	B3	133	B33	4
	215	B4	136	B35	4
	216	B12	132	B28	4
	217	B13	130	B27	4

Table 5. List of Samples. (Localities on figure 19)

Late Glacial Deposits

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.
LGd	218	B9	123	B12	4
Boulder	219	B18	129	B23	4
Clay;	220	B20	120	B9	4
shoreline	221	B23	119	B8	4
samples.	222	B24	118	B7	4
(SO >3.0)	223	B33	117	B2	4

FACIES	CATALOGUE NOS.		WORKING NOS.		
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.

Table 5. List of Samples. (Localities on figure 19)

Soils in the Catchment Area (M.J.Pink's samples)

FACIES	CATALOGUE NOS.		WORKING NOS.			
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD	LOCALITY NO.	TRIP NO.
	224	(fig.	178			
	225	19d)	179			
	226	"	186			
	227	"	180			
	228	"	181			
	229	"	187			
	230	"	189			
	231	"	177			
	232	"	188			
	233	"	191			
	234	"	192			
	235	"	190			
	236	"	183			
	237	"	184			
	238	"	185			
	239	"	182			

FACIES	CATALOGUE NOS.		WORKING NOS.			
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD	LOCALITY NO.	TRIP NO.

Table 5. List of Samples. (Localities on figure 19)

Rocks in the Catchment Area (M.J.Pink's samples)

FACIES	CATALOGUE NOS.		WORKING NOS.			
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.	
	240	(fig. 19d)	148			
	241		162			
	242	"	151			
	243	"	163			
	244	"	164			
	245	"	165			
	246	"	166			
	247	"	152			
	248	"	149			
	249	"	145			
	250	"	167			
	251	"	153			
	252	"	150			
	253	"	146			
	254	"	171			
	255	"	168			
	256	"	147			
	257	"	172			
	258	"	169			

FACIES	CATALOGUE NOS.		WORKING NOS.			
	SAMPLE NO.	LOCALITY NO.	DATA SHEET NO.	FIELD LOCALITY NO.	TRIP NO.	
	259	(fig. 19d)	170			
	260		174			
	261	"	173			
	262	"	193			
	263	"	176			
	264	"	175			
	265	"	155			
	266	"	156			
	267	"	157			
	268	"	158			
	269	"	159			
	270	"	160			
	271	"	161			
	272	"	154			

Figure 19 is to be found folded in at the back of this volume.

Chapter 6. Mathematical Relationships.

(Krumbein and Pettijohn, 1938; Chapter 5)

Particle Size/Settling Velocity Relationships.

The calculation of particle size frequency distributions of both fine and coarse material, as well as the separation of silt and clay fractions, depend on two basic assumptions:

a. That solid particles settling in liquid media reach a constant velocity in negligible length of time.

b. That there is a defineable relation-ship between the size of the particles and this constant settling velocity (or terminal velocity).

This chapter is devoted to outlining the formulae used in other parts of this work.

Symbols.

r: radius of a particle (cms).

d: diameter of a particle (units stated).

η: viscosity of liquid (poise).

σ: solid specific gravity.

ρ: liquid specific gravity.

g: acceleration due to gravity (981 cms/sec).

h: distance a particle settles (cms).

t: time taken for a particle to settle through a distance h.

v: settling velocity (cms/sec).

Fine grained Material. Small particles reach a constant velocity when the fluid resistance equals the constant down-ward force exerted by gravity. Thus it depends on: radius, density, shape, and surface texture of the solid particle, and the density and viscosity of the liquid.

Stokes' Law.

Fluid Resistance to the movement of a small, rigid, smooth sphere which is suspended in the fluid;

$$R = 6\pi r\eta v.$$

Effective Weight of a small sphere acting downwards;

$$= 4/3\pi r^3 \sigma g.$$

Effective Buoyancy of liquid acting upwards;

$$= 4/3\pi r^3 \rho g.$$

Thus the net force downwards when a sphere is settling in liquid;

$$= 4/3\pi r^3 (\sigma - \rho)g.$$

Equilibrium is reached when the sphere reaches its terminal velocity;

$$R = 6\pi r\eta v = 4/3\pi r^3 (\sigma - \rho)g.$$

$$\text{or } v = \frac{2/9(\sigma - \rho)gr^2}{\eta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.$$

This is Stokes' Equation. With d in mm and substituting $v = h/t$, there are three forms of Stokes' Equation used in this study;

a. $$v = \frac{(\sigma - \rho)gd^2}{18\eta \times 10^{-1}}$$

b. $$t = \frac{18h\eta \times 10^2}{(\sigma - \rho)gd^2}$$

c. $$d^2 = \frac{18h\eta \times 10^2}{(\sigma - \rho)gt}$$

The solid particles found in natural deposits are unlikely to be smooth rigid spheres of identical specific gravity. Thus a term is introduced to include these deviations; Schone's Hydraulic Value: The diameter of a smooth rigid quartz sphere having the same settling velocity as a given particle in water.

Thus, unless otherwise stated, solid S.G. is 2.65. Also, particle size distributions are, in fact, "hydraulic value distributions". Further assumptions are:

a. Distance between liquid molecules is negligible compared with particle size; this applies to particles larger than 0.0001 mm (colloidal range). This is not always the case with Windermere material, portions of certain samples remain in suspension indefinately due to Brownian Movement. However this does not cause inherent errors in any of the methods used in this work. The upper limit of application of Stokes' Law is considered in the next section.

b. Factors introduced by wall nearness and the presence of other particles are negligible if the diameter of the settling tube is greater than 5 cms and the solid suspension is dilute (less than 25 gms/L). The hyperbolic curve on figure 20 shows how rapidly wall effects become negligible.

Coarse grained Material. Particles larger than about 0.140 mm diameter do not obey Stokes' Law theoretically. In practice particles larger than 0.200 mm do not even approximately obey it; and the settling velocities of particles larger than 1.55 mm vary with the square root, rather than the square, of the diameters.

Figure 20. Effect of Wall Nearness on Settling Velocities of Spheres.

(Reproduced from Krumbein and Pettijohn, 1939)

A: diameter 0.005 mm.

B: diameter 0.002 mm.

Rubey's Impact Formula.

The fluid (or viscous) resistance to a pebble suspended at a constant height by elutriation is negligible, but the weight of the pebble is supported by the fluid impact of the rising water.

Effective Weight of pebble; $= 4/3.r^3\pi(\sigma - \rho)g.$

Fluid Impact of water; $= \pi r^2 v^2 \rho .$

At equilibrium, $\pi r^2 v^2 \rho = 4/.r^3\pi(\sigma - \rho)g;$

or, $v = \frac{g(\sigma - \rho)d}{15\rho}^{1/2}$ with d in mm.

This is Rubey's Impact Formula. As before particle size distributions are, in fact, "hydraulic value distributions". Solid S.G. is 2.65 unless otherwise stated.

All Grades. The settling velocity of small particles is controlled by viscous resistance ignoring fluid impact ($v \propto d^2$); that of larger particles by fluid impact ignoring viscous resistance ($v^2 \propto d$). Solid particles with diameters between the upper limit of Stokes' Law and the lower limit of the Impact Formula were observed to settle in liquid with velocities that are proportional to a power of the diameter which varies from 2 to 1/2. Assuming that the transition is gradual, a general formula is derived. Thus at equilibrium;

Effective Weight equals Fluid Impact plus Viscous Resistance.

or, $$v = \frac{\left[4/3.g\rho(\sigma - \rho)r^3 + 9\eta^2\right]^{1/2} - 3\eta}{\rho r} \quad \ldots\ldots\ldots 3.$$

This is Rubey's General Formula. Note that the size is expressed as r in cms; d in mm can be calculated from this. Assumptions are made as before. The relationship of this General Formula to the other two is shown on figure 21.

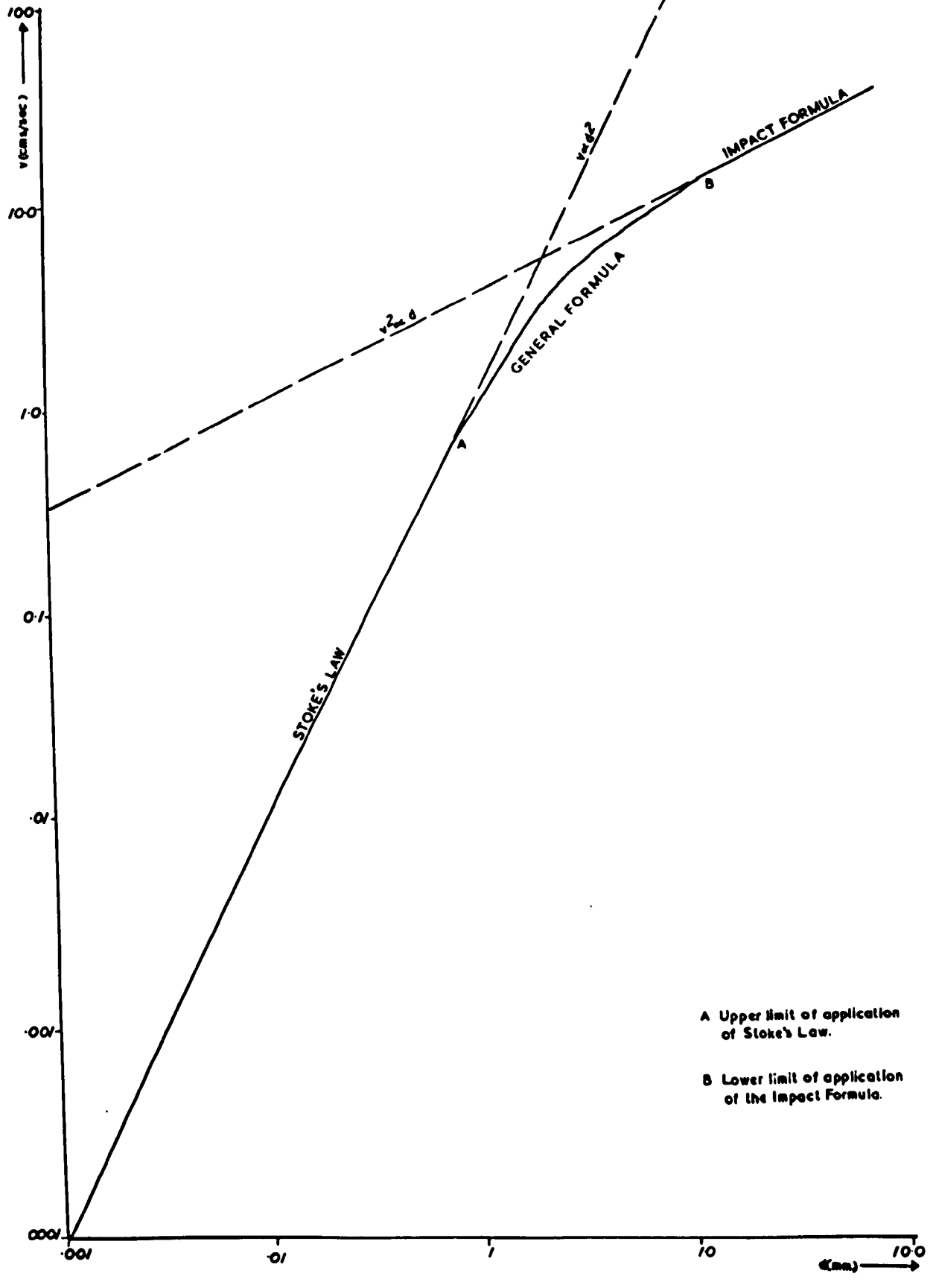


Figure 21. Particle Size (Hydraulic Value) / Settling Rate Relationships at 20°C for Distilled Water.

Sedimenting Systems.

Stokes' Law concerns only individual small particles; suspensions are now considered which consist of a number of these.

Homogeneous Monodisperse Systems.

All particles are of identical settling velocity. Two assumptions are made:

a. Suspensions are infinitely dilute.

b. Temperature is constant.

p is the weight of material settled from suspension, height h. P is the total weight in suspension.

$p = k\frac{Pvt}{h}$, (where k is constant);

$h = vt$; $p = kP$. Therefore $k = 1$ when all material has settled. Thus the weight of material settled out of mono-disperse suspension in time t is:

$p = \frac{Pvt}{h}$;.....4.

Homogeneous Polydisperse Systems.

A series of monodisperse systems in which the size (radii) of successive systems varies by infinitesimals. Each system (or fraction), having a given radius, settles as a unit. At time t, p(t), the amount of material settled, consists of two broad units:

a. Fractions that have completely settled, in which $v > h/t$, termed w.

b. Some part of the fractions that have not completely settled, in which $v < h/t$. The weight of each fraction here is: $\frac{Pvt}{h}$ (equation 4).

$P = F(r)dr$; because the radii vary by infinitesimals.

$$p = \frac{F(r)r^2\,dr.Ct}{h};\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.$$

Where $C = \frac{2/9.(\sigma - \rho)g}{\eta}$; Stokes' Law.

When a fraction has completely settled,

$p = F(r)dr$; for that fraction.

Thus $r = h/Ct.^{1/2}$ .....6.

r, at time t, is the radius of particles in that fraction that has just settled completely.

$$\text{Thus } p(t) = \int_0^{r=h/Ct.1/2} \left[\frac{F(r)dr.\ Ct.\ r^2}{h}\right] + \int_{r=h/Ct.1/2}^{\infty} [F(r)dr].$$

The first integral consists of fractions with radii smaller than r. The second of fractions with radii larger than r; termed w above.

$$\text{Thus } \frac{dp(t)}{dt} = \int_0^{r=h/Ct.1/2} \left[\frac{F(r)dr.\ C.\ r^2}{h}\right];$$

$$\text{and } \frac{tdp(t)}{dt} = \int_0^{r=h/Ct.1/2} \left[\frac{F(r)dr.\ Ct.\ r^2}{h}\right]; \quad = \int_0^{r=h/Ct.1/2} [p].$$

Thus the weight of the smaller unit is $\frac{tdp(t)}{dt}$ at time t.

$$p(t) = w + \frac{tdp(t)}{dt} \qquad = w + \frac{dp(t)}{d.lnt}$$

Thus, the weight of material settled in time t;

$$p(t) = w + \frac{tdp(t)}{dt};\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.$$

This is Oden's Formula for Polydisperse Systems.

Separation of Silt and Clay.

(Truog et al, 1936.)

The condition for separation is that every silt particle should have just settled from suspension before the supernatant liquid is removed. Particles of diameter 0.002 mm.,

initially at the top of the suspension , are considered. The time T for these to settle to the bottom of the suspension is calculated. When a centrifuge is used, the spinning is manipulated to stop at the same time as these particles reach the bottom of the centrifuge. All the silt will then have settled along with some clay (fig. 22).

In a horizontal centrifuge: $g = r\omega^2$;

where ω, angular velocity, $= 2\pi f$ (radians/sec.);

where f is centrifuge frequency (revolutions/sec.).

$$g = 4\pi^2 f^2 r;$$

$$\text{and } v = \frac{d^2 (\sigma - \rho) 4\pi^2 f^2 r}{18\eta \times 100};$$

substituting for g in Stokes' Equation. For one spinning operation, d, η, σ, ρ, and f are taken as constant; v increases as r increases (particles move outwards).

$$v = kr; \quad \text{where } k = \frac{d^2 (\sigma - \rho) 4\pi^2 f^2}{18\eta \times 100};$$

$$\frac{dr}{dt} = kr; \quad \frac{dr}{r} = kdt;$$

$$\sum_{r(0)}^{r(F)} [\ln r] = k \sum_{r(0)}^{r(F)} [t].$$

r(F) is the distance from the centre of the centrifuge to the top surface of the liquid.

r(0) is that to the bottom of the tube.

$$\ln \frac{r(F)}{r(0)} = k(t - t_0).$$

$$\text{Thus } T = \ln \frac{r(F)}{r(0)} / k; \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 8.$$

The manipulation of the centrifuge is now considered. T is the time required to throw down all the silt at a frequency of f; but the centrifuge takes some time to reach this frequency after being switched on, and further time to stop spinning

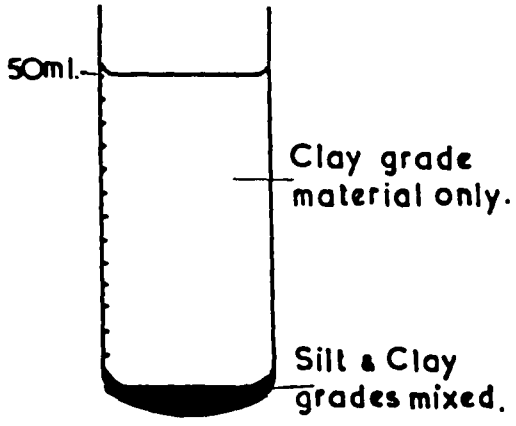


Figure 22. State of Suspension in Centrifuge Tube After Spinning.

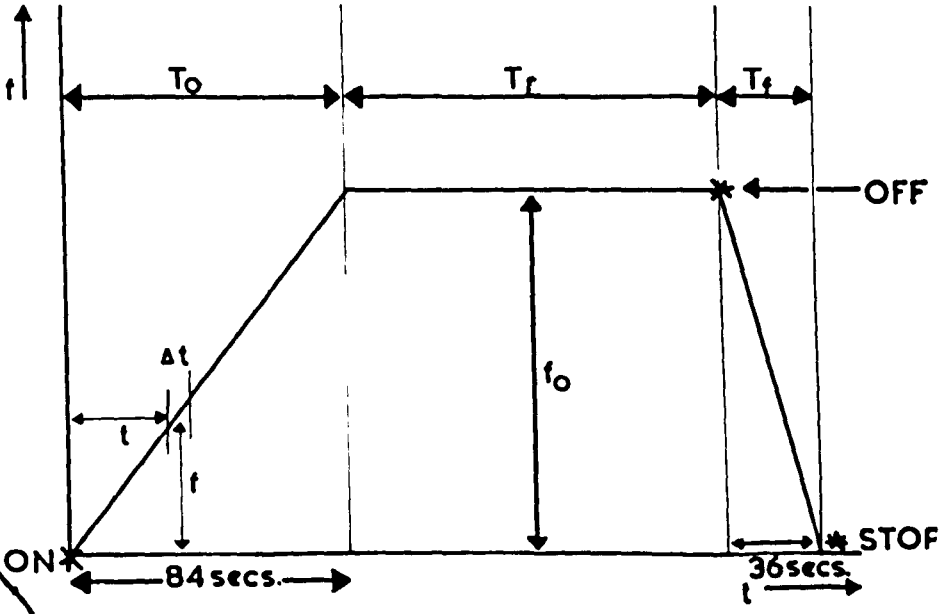


Figure 23. Hypothetical Angular Velocity Diagram for Centrifuge.

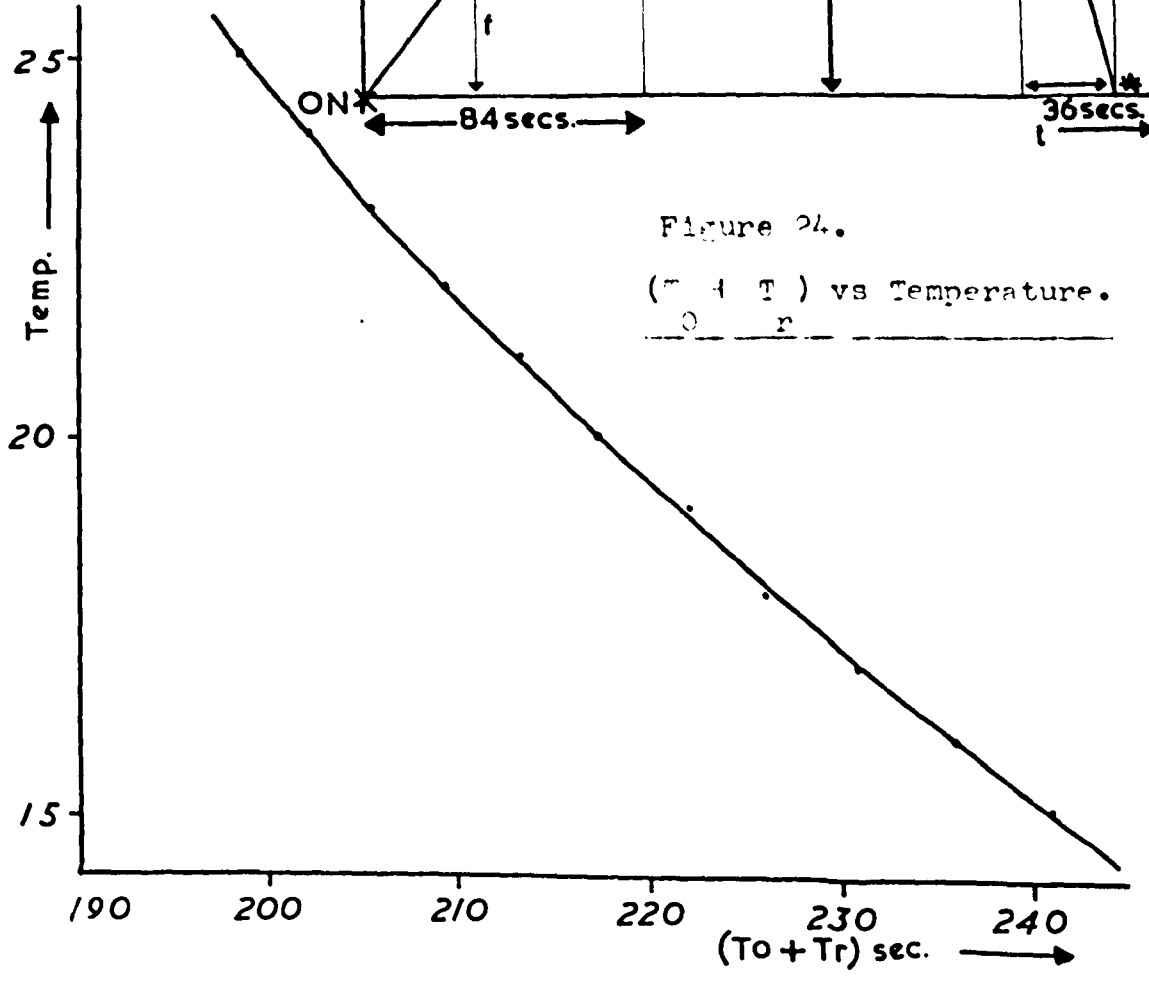


Figure 24.

(+ T) vs Temperature.
o r

after being switched off. T'_0 the equivalent length of time at f revs/sec for T_0 the running up time, T_r the actual time of running at f revs/sec, and T_f the running down time are calculated. Acceleration and deceleration are assumed to be linear (fig. 23). T'_0 and T'_f are the effective times, corresp-onding to T_0 and T_f, at the frequency f at which T_0 and T_f are calculated. The centrifuge spinning at f revs/sec for T seconds is equivalent to its spinning at f_0 for T'_0.

$$T'_0 = \Delta t\left[\frac{f}{f_0}\right]^2 \qquad f \propto t \text{ because the graph is linear.}$$

$$f = \frac{f_0}{T_0}\, t \;;$$

$$\text{Thus } \Delta T'_0 = \Delta t.\left[\frac{f_0\, t}{T_0 f_0}\right]^2 = \frac{\Delta t.[t]^2}{[T_0]} \;;$$

$$T'_0 = \int \Delta T'_0 = \int \left[\frac{t}{T_0}\right]^2 .\Delta T = 1/3.T_0$$

$$\text{Likewise } T'_f = 1/3.\, T_0 \;;$$

$$\text{and } T'_0 = 1/3.(T_0 + T_f) \;; \ldots\ldots\ldots\ldots\ldots\ldots 9.$$

For silt separation, $T = T' + T_r$;

$$T_r = T - 1/3.(T_0 + T_f)$$

Values for T_0 and T_f, with the frequency at 1000 revs/min, are shown in table 6. (N.B. Four 50 ml tubes were filled to the mark and used in these tests.)

$T' = 40$ and $T_r = (T - 40)$ from equation 9.

T is calculated from equation 8 for distilled water. $T_0 + T_r$ is the most convenient time for manipulation of the centrifuge. This was plotted against temperature (table 7 and fig. 24).

Settling bottle times are calculated from Stokes' Law.

Table 6. Centrifuge. (Time in seconds.)

	1	2	3	Average.
To.	84.0	85.0	83.0	84.0
Tf.	36.0	36.0	36.0	36.0

Table 7. Centrifuge. (Time in seconds.)

Temp. (°C.)	Viscosity. (Poise.)	T.	Tr.	Tr+84.
15.0	0.01143	197	157	241
16.0	0.01115	192	152	236
17.0	0.01085	187	147	231
18.0	0.01058	182	142	226
19.0	0.01032	178	138	222
20.0	0.01006	173	133	217
21.0	0.00982	169	129	213
22.0	0.00958	165	125	209
23.0	0.00935	161	121	205
24.0	0.00915	158	118	202
25.0	0.00894	154	114	198

Chapter 7. Miscellaneous Analyses.

Rapid analyses were made to determine the pH, water content and organic content of the deposits (fig. 9). These results are of some importance with respect to certain aspects of sedimentation in the lake. However it is emphasised that a detailed limnological study of the lake water and sediments was not made here. The results already obtained by previous authors working on Windermere material are discussed in the appropriate sections of this thesis. The removal of organic matter is of wider importance, discussed in this chapter.

pH Measurements.

A portable pH meter was used. After initial calibration the unconsolidated material was probed with the sharp glass probe and the galvanometer readings are a direct measure of the pH. Laboratory readings were found to be similar to those from the same material in the field after sampling so pH measurements were generally taken in the laboratory.

Water Content.

Wet weight was compared with that after drying in the oven at 95°C. Water contentwas expressed as a percentage of wet weight. The oven temperature was not higher than 100°C as interstitial water only was being driven off, not loosely held molecular water which is driven off at about 130°C. These analyses were not very successful because of uncertainty about the original condition of many samples when examined in the laboratory. The water content of the ooze was not taken for this reason; nor was that of samples which appeared to have dried in transit due to a faulty seal on the storing bottles.

Organic Content.

Pennington (1947a) has noted that surface ooze and gyttja are effectively altered by the presence and nature of the organic matter; that there are two distinct types of this: discrete particles and non vegetable organic compounds such as polysaccharides; and that these latter have important effects on both the mechanical properties (such as flocculation) and the chemical properties (such as pH). Richardson (1941) showed that the discrete particles of vegetable matter have settling properties similar to those of the mineral particles. For this work it was therefore necessary to devise a method for studying the sedimentary properties of the organic lake deposits, accounting for both the mineral particles and the vegetable particles as well as the organic gel floccule matrix. This section is concerned with the method for removing organic matter from the samples both to measure the organic content as a percentage and to produce a representative organic free portion for sedimentary study in the laboratory. The technique used should alter the mechanical properties of the minerals present by a minimum. A series of tests were devised for this purpose using the test samples described below.

Descriptions of Test Samples.

These four samples were used for routine tests for accuracy and reproducibility of the techniques and apparatus throughout the work. Only three of them are used in this section on removing organic matter but all are described.

Test Sample 1. (Sample No. 10)

Top of Core No. 2. 200 ml grey ooze, leaves and a fine

silty material were clearly visible. Proportion by weight larger than 0.064 mm: 12.5%.

Test Sample 2. (Sample No. 175)

Bottom of Core No. 4 . 200 ml of pale grey sand facies in the Late Glacial laminated sequence; dark angular fragments were seen and the core exhibited minor wrinkled structures. Proportion by weight larger than 0.064 mm: 14.7%.

Test Sample 3. (Sample No. 207)

100 gms (dry) pale khaki smooth unlaminated fluvio-glacial clay from the sediment surface in the shallow "threshold" region between the North and South Basins (Appendix No. 2). Proportion by weight larger than 0.064 mm: 14.5%.

Test Sample 4.

200 gms (dry) yellow quartzose sand collected from a building site in University College.

Techniques for Removing Organic Matter.

(N.B. Tested after initial separation of coarse and fine material and drying.)

Physical Separation of Mineral and Organic Particles.

Elutriation. Test Sample 1 (T1) was used . A portion of the coarse fraction was placed in a litre separating funnel supported in a retort stand in the sink, with a rubber connection between the cold tap and the stopcock at the base of the funnel. The test was facilitated by the visual distinction between mineral and vegetable particles in suspension; it was not attempted with fine material. At first, medium sized vegetable debris was removed along with fine mineral particles. The current was decreased until the finest

mineral particles were suspended at the top of the funnel without being carried off and it was maintained at this until no further organic matter was being removed. The material in the funnel was dried and sieved; the finest organic matter was found in Sieve Mesh 85, indicating that mineral particles of 0.064 mm diameter and vegetable particles of approximately 0.178 mm "diameter" are removed by the same elutriating current. This process was continued removing the coarsest possible vegetable matter by elutriation before sieving and retaining the finer mineral material freed of organic matter; until the latter is completely removed. This technique provided ideal organic free and otherwise unaffected portions but it could only be used for coarse material and it was time consuming. It was not generally used in this study.

Heavy Liquid. Adjustments were made to the specific gravity of a bromoform/acetone mixture in the hope that the mineral matter would sink and the organic matter float thus providing a physical separation. The method was not successful, probably because it was not possible to completely disaggregate, disperse, and wet the particles before separation, particularly with the fine fraction, but also with the coarse fraction. Centrifuging was no more successful.

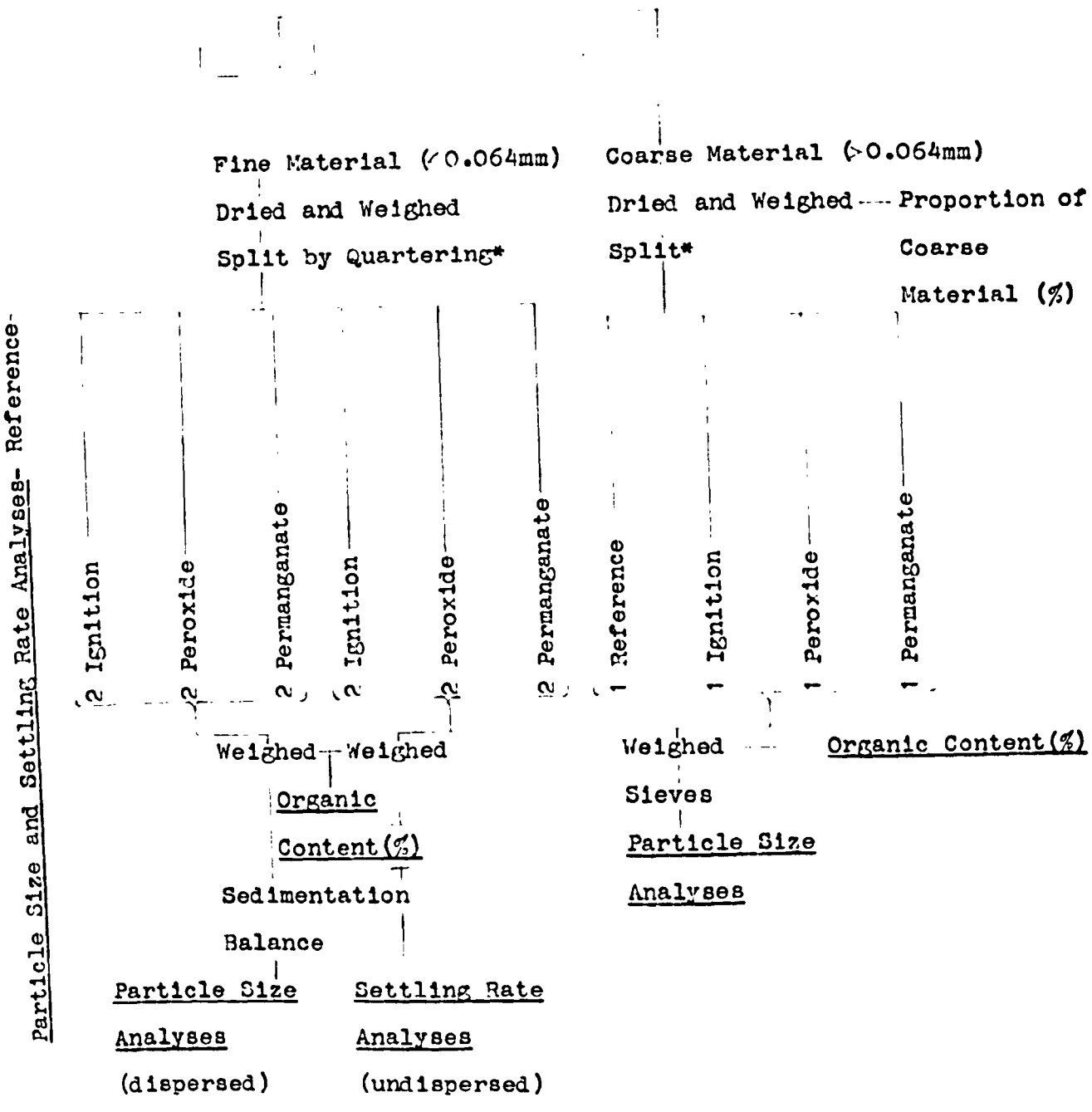
Oxidation of Organic Matter.

Three methods were tested: 10% Hydrogen Peroxide, Alkaline Potassium Permanganate (0.05N; pH 12), and Ignition. The first two were performed in the oven at about 50°C, the third was performed in nickel crucibles over the strongest oxidising bunsen flame (approximately 700°C). Tests were done

using T1, T2, T3. T1 was used to discover when the organic matter had been removed completely (portions reached constant weight). T2 and T3, the clays, were used as "blanks". Oxid--ation was complete after 30 minutes of ignition and 3 days of peroxide and permanganate treatment. The flow sheet for these tests is shown on figure 25. The results of the weight loss, mechanical analyses (coarse fraction), and mechanical analyses (fine fraction dispersed and undispersed) tests are listed in table 8.

Conclusions and Standardised Procedure.

The physical separations which would have been ideal were not practicable for reasons already given. The three oxidation processes were successful in removing organic matter from both fractions (T1 reached constant weight - table 8a). Mineral mechanical properties were, in fact, altered to a greater or lesser extent by oxidation (T2 and T3 - table 8b,c,d). This was expected when it was seen that the material had become a rusty red colour, probably due to iron and manganese passing to the higher valency states. A chemical change in some minerals and, possibly, a complete breakdown of others is expected to alter specific gravity and flocculation properties and thus mechanical distributions. However, on the basis of the tests, peroxide and ignition were seen to have similar effects on mineral mechanical properties of T2 and T3; permanganate caused spurious results in all but the coarse material. Ignition was used throughout this work for conven--ience, and the resulting mineral material used for particle size analyses. These results were slightly inaccurate, but less so than undispersed analyses. Standardised Technique - figure 26.



* The processes of sample splitting ~~is~~ are considered in Chapter 9.

N.B. Permanganate is washed out with distilled water, centrifuging several times.

Figure 25. Tests for Removing Organic Matter - Flow Sheet.

Table 8. Removal of Organic Matter - Results of Tests.

a. Percentage Weight Loss and Gain.

	Sample T1		Sample T2		Sample T3	
Process	Coarse	Fine	Coarse	Fine	Coarse	Fine
Ignition	-12.85	-22.20	-3.60 *	-4.50 *	-3.40 *	-3.20 *
KMnO4	-24.20	-39.70	-13.30	-28.80	-14.70	-19.90
H2O2	-7.40	-7.50	+2.05	+4.50	+3.65	+2.10

Considered Samples T2 and T3 where, ideally. there should be zero weight loss or gain, ignition and peroxide treatments are equally satisfactory.

* This confirms Pennington's Hypothesis (1943) that molecular water (3.5 percent approximately) is driven off during ignition.

b. Coarse Material - Particle Size Distribution.

(Weight Percentage Oversize.)

Sieve Mesh	Sample T2				Sample T3			
No.	Ref.	Ign.	H2O2	KMnO4	Ref.	Ign.	H2O2	KMnO4
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36	2.0	2.1	2.2	2.0	0.0	0.0	0.0	0.0
52	2.5	2.4	2.5	2.6	0.0	0.0	0.0	0.0
72	3.5	3.2	3.0	3.4	0.5	0.2	0.3	0.5
85	5.0	4.5	4.8	4.7	1.1	0.8	0.6	0.9
100	8.0	7.8	7.7	7.9	2.5	2.4	2.4	2.2
150	30.0	28.5	28.2	29.5	16.0	16.4	16.2	15.8
200	83.5	83.4	81.2	80.7	77.2	78.3	77.9	78.1
240	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The three processes are equally satisfactory in this respect.

Table 8. c. Fine Material - Particle Size Distribution.

Phi Values. (fig. 37)	Sample T2				Sample T3			
	Ref.	Ign. (Av.)	H202 (Av.)	KMnO4 (Av.)	Ref.	Ign. (Av.)	H202 (Av.)	KMnO4 (Av.)
4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.0	4.0	4.5	4.0	5.0	0.6	0.9	0.7	0.0
6.0	18.5	16.5	16.0	18.5	3.2	3.3	3.2	0.9
6.5	30.5	28.0	28.5	26.5	7.1	6.8	7.4	3.0
7.0	46.5	44.0	43.5	41.0	12.6	11.8	11.8	6.8
7.5	65.0	62.0	63.0	63.0	21.0	20.3	21.9	13.9
8.0	86.0	83.5	82.5	88.5	33.4	32.1	33.7	23.1
8.5	94.5	91.5	91.0	96.0	42.2	42.2	43.1	35.0
9.0	98.5	96.0	95.5	99.0	53.1	51.2	52.7	44.7

Both ignition and peroxide treatments appear equally satisfactory in this respect; not permanganate treatment (especially with T3).

d. Fine Material - Settling Rate Distribution.

(Weight Percentage Oversize.)

Log_{10} V (cms/sec) (Chap.)	Sample T2				Sample T3			
	Ref.	Ign. (Av.)	H202 (Av.)	KMnO4 (Av.)	Ref.	Ign. (Av.)	H202 (Av.)	KMnO4 (Av.)
-0.45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.05	2.5	2.0	1.5	0.5	0.0	0.0	0.0	0.0
-1.65	21.5	20.5	20.0	14.5	3.0	3.0	3.2	1.5
-1.95	36.5	35.5	33.5	32.0	9.2	9.3	9.2	5.5
-2.25	68.0	64.0	65.0	55.0	15.1	15.7	15.6	9.1
-2.55	84.0	74.5	74.0	67.0	27.0	26.3	27.1	15.9
-2.85	93.5	85.0	81.5	75.0	39.9	39.1	38.2	26.9
-3.15	98.5	89.5	87.5	82.5	51.6	51.0	52.0	39.0
-3.45	100.0	94.5	94.0	89.0	61.0	60.7	60.3	52.3

None are completely satisfactory; ignition and peroxide treatments are more so than permanganate, in this respect.

Dry Subsample Disaggregated (Prior to separation)
|
Approx. 10 gms weighed accurately in a nickel crucible
|
Ignited over oxidising bunsen flame for 30 minutes
|
Cooled in a dessicator
|
Weighed and Organic Content calculated (percent)
|
Retained for Mechanical Analyses

N.B. Calculation of Organic Content by this method:
Pennington (1943) claims that there is an inherent weight loss of approximately 3.5 percent after ignition due to the driving off of sorbed molecular water from the mineral matter. This conclusion is supported by the results in table 8a.

$\therefore$ Organic Content = Percent wt. loss - 3.5.

Figure 26. Flow Sheet for the Removal of Organic Matter by Ignition.

PART IIB. PHYSICAL ANALYSES.

Chapter 8. Preliminary Mechanical Studies.

These first samples, surface ooze and clay from the shallow "threshold" region, are regarded as preliminary for the following reasons:

a. The "spot sampling" technique was not devised at this stage so these are not strictly comparable with later samples.

b. They were examined before the full flow sheet of techniques was devised or all the apparatus was available. Thus, for example, coarse material was separated from fine material with Sieve Mesh 200 with an aperture diameter of 0.076 mm instead of Mesh 240 (0.064 mm); and the fine material was not examined at all because the Sedimentation Balance was not available. The flow sheet is shown in Appendix No. 3.

The sampling localities are charted and catalogued in Appendix No. 2. They were not given catalogue locality or sample nos. N.B. Twelve of them were, in fact, fully examined at a later stage; there was sufficient material in these cases and they provided a third "facies" of surface ooze (January 1961).

The results are tabulated in Appendix No. 3. They were found useful as a guide to subsequent mechanical work as follows:

a. Proportion of "sand" in the ooze is highest near river mouths ($> 30\%$); moderate in shallow water areas near to the shoreline (3 - 10%); and low in deep water in the middle of the lake ($< 3\%$) as well on the shallow "threshold" region.

b. The proportion of "sand" in the shallow water clay deposits is more variable than that in the ooze. In some cases it is more than 25% and in others it is less than 1%.

c. The median diameter of this "sand" is in the "fine sand range" (Wentworth, 1922), approximately 0.120 mm, and varied only slightly from place to place in the ooze. It showed a slight tendancy to be larger near river mouths. It is extremely variable, however, in the clays varying from the "coarse sand range" (> 0.600 mm) to fine sand.

d. The sorting values are generally low (< 1.70) though certain clays are noteably higher than this (> 2.00). Skewness and kurtosis were not examined at this stage.

e. Roundness analyses generally showed that the fine "sand" material is angular and that these results are of no correlative value. N.B. It is shown in a later chapter that results from coarser material are valuable in this respect.

f. The organic matter is not important in the clays but appeared to be important in several properties of the flocculating ooze, particularly fine grained material; this was not examined in detail at this stage. It was noted that "leaf beds", with up to 100% organic matter (leaves and twigs) graded into normal ooze and these were examined where appropriate.

It was concluded, after this preliminary work, that the mechanical data of coarse material are of some interest and correlative value. It was thus foreseen that a full mechanical analysis of material from all over the lake, with emphasis on organic matter, would provide important results.

Chapter 9. Apparatus.

Sedimentation Balance. (Gallenkamp's Cat. No. PC650)

This provides an indirect method for measuring particle size and settling rate distributions of fine material. The balance itself provides data for plotting a curve of sediment weight, settling out of homogeneous suspension, against time. Initially the liquid suspension of the material being examined is shaken up so that the discrete settling units (particles or floccules) are uniformly distributed throughout the liquid. Applying Oden's Formula (see Chapter 6):

$$w = p - \frac{dp}{d\ln t};$$

where w is the weight of the material greater than or equal to that settling from top to bottom of the suspension in time t; p is the weight on the balance pan after time t. The height of the suspension h is measured and p and t are known. Thus w and hence the weight percentage oversize settling faster than h/t can be calculated. This settling velocity distribution is related to particle size by Stokes' Law.

Range of Application.

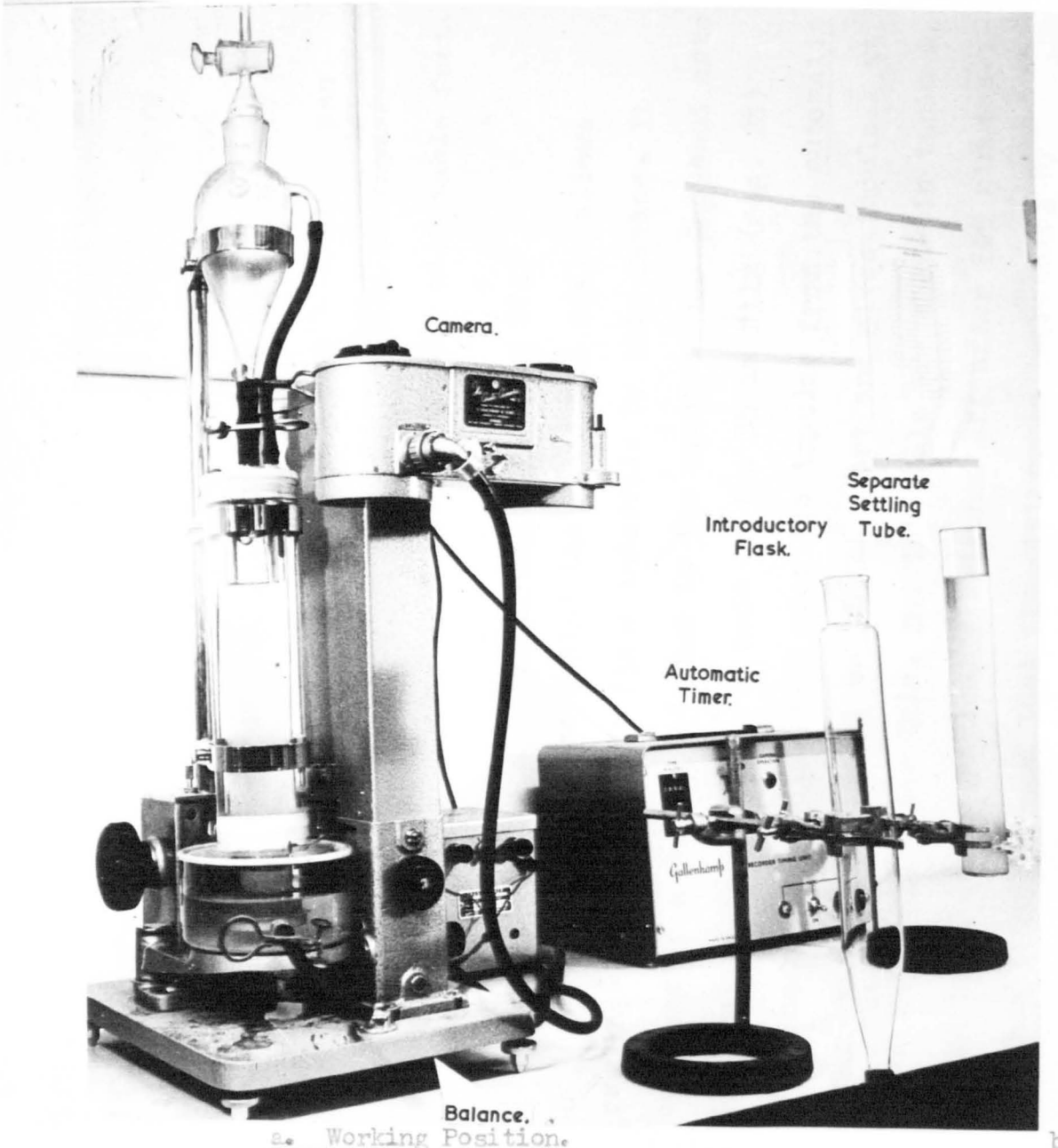
The range of Stokes' Law and practicability are the two factors considered. Particles of sizes near the upper limit of Stokes' Law settle through the comparatively short suspension in such a short time that initial readings may be seriously affected by the small timing errors which arise normally. The upper limit is thus set by the manufacturers at 0.076 mm; generally, in this work, the upper limit is 0.064 mm. Particles in the lower range of Stokes' Law settle sufficiently slowly for temperature fluctuations to become serious and the

lower limit is set by the manufacturers at 0.005 mm. This means, in effect, that the balance should not be left for more than nine hours. Unfortunately, the material being examined in this study generally contains a high proportion smaller than this. There are no inherent errors but it does lead to incomplete analyses (Chapter 13).

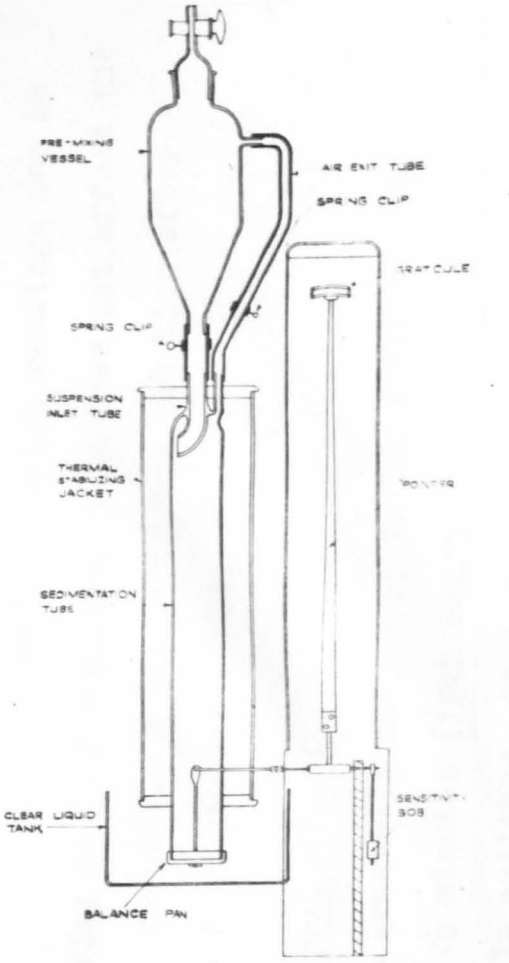
The Balance. (figs. 27a, b)

This has been fully described by Cohen (1959). It consists of a vertical sedimentation tube 30 cms high and 5 cms in diameter which is sealed inside an outer thermal stabilising jacket. The bottom of the inner tube fits loosely inside the rim of a circular balance pan suspended on a torsion wire in a clear liquid tank which is filled with the same liquid as the liquid suspension. Material settling out of suspension onto the pan causes the torsion wire to move a graticule scale (-10 to 105 marked in units of 1) by an amount proportional to the weight of settled material. The pan is clamped and the apparatus needs recalibration to start at zero for each analysis. The sensitivity can be adjusted by a sensitivity bob at the back of the instrument. This is necessary when either the specific gravity (norm: 2.65) or the concentration of solid in suspension (norm: 2 gms/litre) varies; this adjustment is required to give optimum sensitivity.

Operation. Approximately 225 ml suspension is poured into the pre — mixing vessel above the settling tube from the introductory flask and the former is closed with the stopcock at the top. The suspension is introduced down into the tube by opening both the spring clips on the rubber connections to the pre — mixing vessel. The closed air pressure system holds the



a. Working Position.



b. Diagrammatic (from Cohen, 1959).

Figure 27. The Sedimentation Balance.

liquid inside the tube, thus the stopcock at the top must be closed before the operation starts. The suspension should fill the tube to a height of between 24.0 and 26.0 cms where it is calibrated in mm. The suspension inlet tube is turned outwards at its lower end so that the liquid is thoroughly mixed when it enters the tube. Immediately the balance pan is unclamped to start the analysis. The balance is kept steady with a built in spirit level and four adjustable feet.

The Automatic Camera Recorder. (fig 27a)

A light source behind the graticule scale allows readings to be taken at fixed intervals by this device. It consists of a camera attached to the eyepiece and focussed onto the scale. An exposure is made on the 35 mm film (fig. 28) when the camera recieves an electric impulse from the automatic timer which is switched on at the start and gives impulses at fixed intervals after this. The intervals are shown in table 9, column 1; it is automatically switched off after 525 minutes. Donoghue (1956) showed that time intervals increasing by multiples of $2^{1/2}$ lead to improved accuracy. The operation of of this timer limits the intervals at which readings can be taken to multiples of half a minute, this does not affect the accuracy of the results. A guage records the time after the start in half minute intervals.

Procedure.

It was generally necessary to leave the suspensions settling for 362½ minutes (19th reading); overnight analyses are automatically switched off. The film is wound on between analyses and developed after four had been completed. The

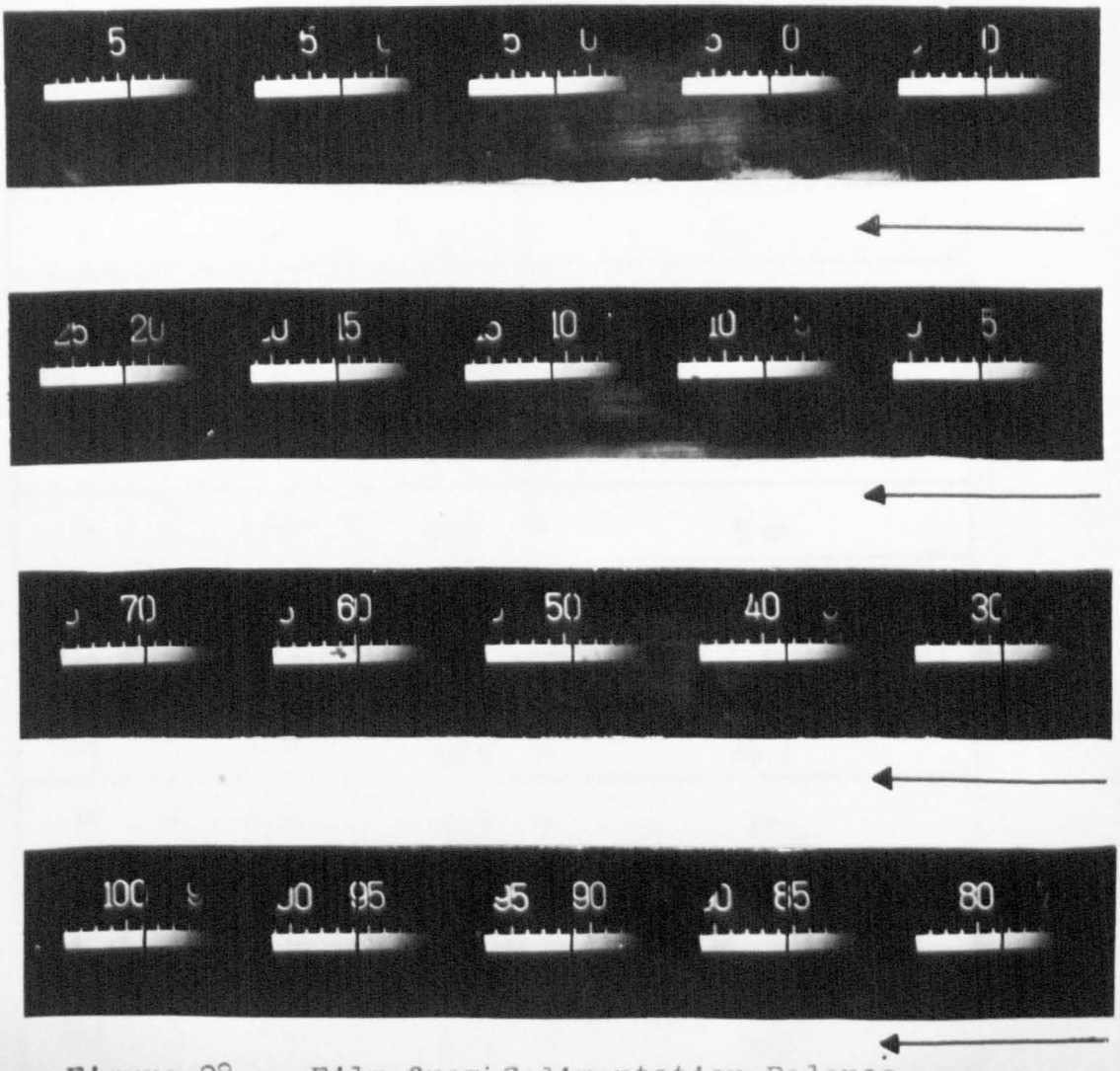


Figure 28. Film from Sedimentation Balance.

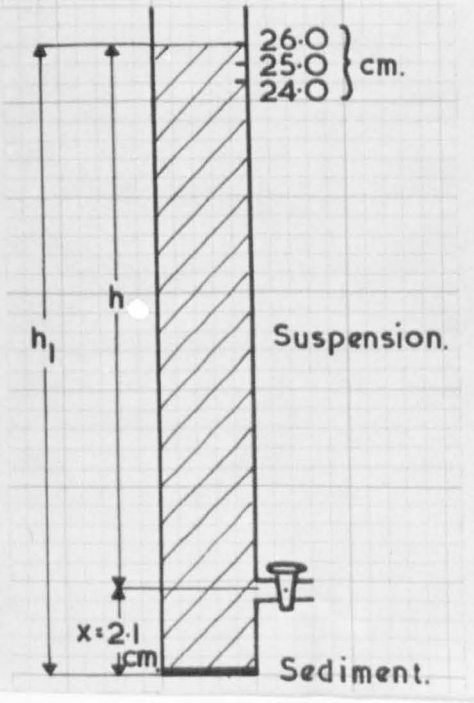


Figure 29. Diagram of the Separate Settling Tube.

Table 9. Data Sheet for Sedimentation Balance Results.

CALCULATIONS

1	2	3	4
Time (mins)	ln t (t in secs)	Reading (fig. 28)	% by weight deposited
½	3.40	0·3 X	0·884 = 0·3
1	4.10	1·4	" 1·2
1½	4.44	2·1	" 1·9
2	4.79	3·0	" 2·7
3	5.13	4·2	" 3·7
4	5.48	5·7	" 5·0
5½	5.82	7·4	" 6·5
8	6.17	11·0	" 9·7
11½	6.51	15·9	" 14·1
16	6.87	21·7	" 19·2
22½	7.20	29·1	" 25·7
32	7.55	38·5	" 34·0
45½	7.89	49·4	" 43·7
64	8.25	60·0	" 53·0
90½	8.59	69·7	" 61·6
128	8.94	78·4	" 69·3 (Table 16): $\frac{69·3}{78·4}$ = 0·884
181½	9.29	85·5	" 75·6
256	9.64	91·0	" 80·4
362½	9.99	95·8	" 84·7
512	10.34	99·0	" 87·5
		—	
∞	∞	—	100.00

readings are recorded on the special data sheet (table 9, column 3), the films labelled and stored. The glassware is washed between analyses and the instrument recalibrated each time. N.B. The silicone liquid repellant used to coat the inside surfaces of all glassware needs replacing occasionally due to contamination.

The Separate Settling Tube. (figs. 27a and 29)

This was made in the Chemistry Dept.,U.C.L.

The readings on film are directly proportional to, not equal to, w at time t when each reading is exposed. These readings are converted to absolute weight percentages by one of the following two methods:

a. The reading after all the solid has settled out of suspension is constant and it corresponds to 100% of w, the other readings are converted to percentages in the same proportions. This method is simple and accurate, but time consuming because many Windermere samples took several days to settle, colloidal material remains in suspension indefinately. This method was not used here..

b. The separate settling tube is used for a concurrent analysis to be carried out with the identical suspension. The second tube is 5 cms in diameter and 35 cms high, the outlet tap is about 2.0 cms above the base and the tube is graduated in mm between 24.0 and 26.0 cms above this tap. The suspension left over from the main analysis (600 ml is sufficient for both) is is used to fill the second tube to a height h above the tap which is the same as h in the main tube. The tap is opened after a time t, which corresponds to one of the fixed time intervals. x the height of liquid left in the tube was 2.1 cms.

The settled material is not disturbed by the liquid running out, and the time taken for the tube to empty itself is negligible. Thus the second suspension is never left for less than 32 mins (12th reading). All the material left in the tube is washed out, centrifuged, dried, and weighed; this weight is w_1. The total weight of solid is w_0; it is calculated knowing the volume (height to volume conversions, table 10) and its concentration. The percentage p deposited in time t from a column of total height h is:

$$p = \frac{w_1 - x/h_1 \cdot w_0}{w_0 - x/h_1 \cdot w_0} \cdot 100; \text{ where } h_1 = (h + 2.1) \text{ cms.}$$

This corresponds to the reading from the main analysis at time t. The conversion ratio is calculated and applied to all the readings on film giving a series of values of w (table 9, column 4).

The Emery Settling Tube. (figs. 30a, b)

This was made in the Chemistry Dept., U.C.L.

Comparison with Sedimentation Balance.

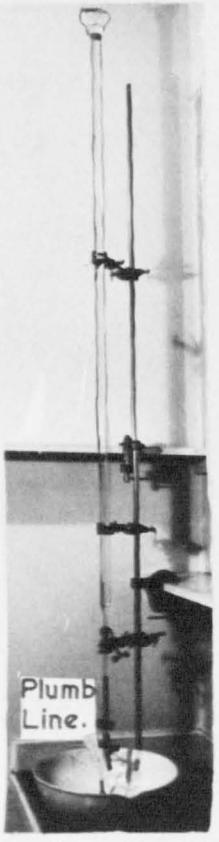
This is a method for measuring mechanical distributions of coarse material

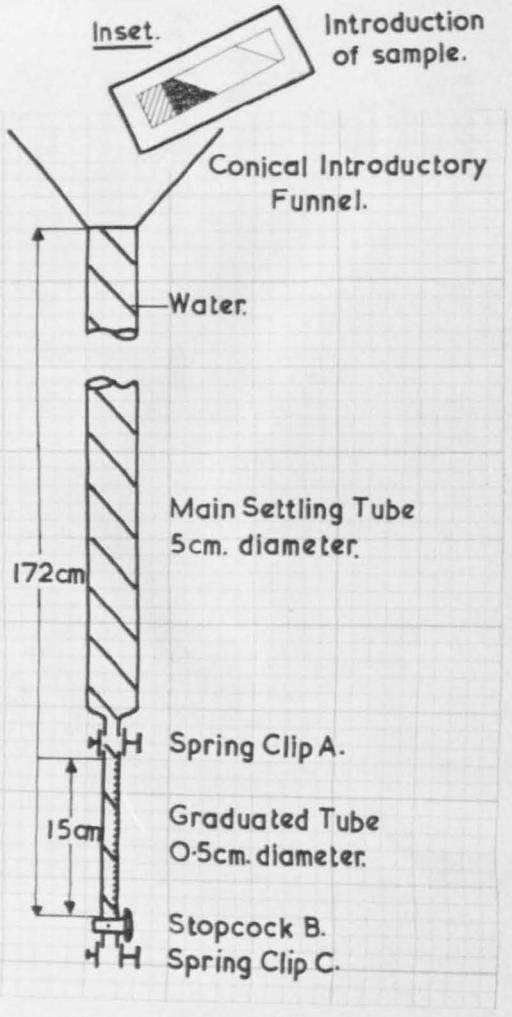
The material being analysed is introduced at the top of the tube at the start in contrast to the homogeneous susp--ensions in the Sedimentation Balance.

Data is obtained by measuring increasing height of material as it settles into the narrow graduated tube at the base of the main tube. Height is approximately proportional to volume which, in turn, is approximately proportional to weight.

Table 10. Separate Settling Tube - Heights and Volumes.

Height (cms)	Volume (ml)
26.0	276.3
25.9	275.3
25.8	274.3
25.7	273.3
25.6	272.3
25.5	271.3
25.4	270.3
25.3	269.3
25.2	268.3
25.1	267.3
25.0	266.3
24.9	265.3
24.8	264.3
24.7	263.3
24.6	262.3
24.5	261.3
24.4	260.3
24.3	259.3
24.2	258.3
24.1	257.3
24.0	256.3





a. In Position. b. Dimensions.

Figure 30. The Emery Tube.

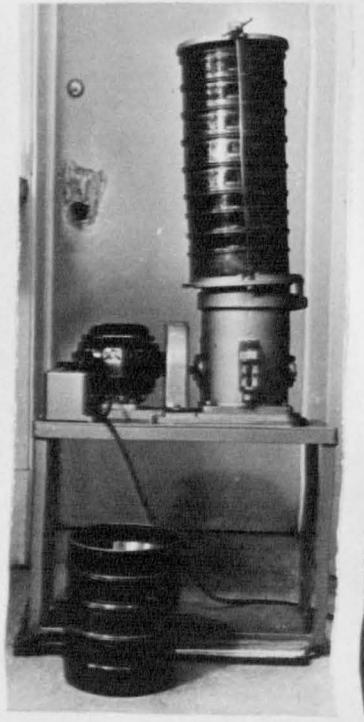


Figure 31. The Sieves and Shaking Machine.

Figure 32. The Use of the Wet Sieving Apparatus.

Thus, provided particle S.G. is homogeneous, Emery Tube and Sedimentation Balance furnish comparable data.

The time taken for an Emery Tube analysis is short (30 minutes) compared to the Sedimentation Balance. Time intervals are thus taken off a stop watch, arbitrarily, to correspond to $\log_{10}$ settling velocity values of:
1.00, 0.75, 0.50, 0.25, 0.00, -0.25, -0.50, -0.75, -1.00;
assuming a water height of 172 cms. This logarithmic scale is comparable with the $2^{1/2}$ scale of the Sedimentation Balance.

The settling height is necessarily greater in the Emery Tube than in the Sedimentation Balance.

Range of Application.

The upper limit is 1.00 mms, set by the stopcock opening at the base of the graduated tube. Thus material larger than Sieve Mesh 18 (0.850 mm) was extracted before analysis. Poole et al (1951) claim that the mass effects of material larger than 1.00 mm cause inaccurate settling data. No material analysed in the Emery Tube, therefore, is governed by the Impact Formula. The lower limit is 0.064 mm, smaller material being analysed in the Sedimentation Balance; this finer range of coarse material is governed by Stokes' Law, and the rest by Rubey's General Formula. This formula is used for all conversions to particle size data.

The Instrument. (fig. 30b)

Emery (1937, 1938) and Hulsey (1961) have described the tube. It is of glass filled with water 172 cms high and 5 cms in diameter, with a funnel at the top for introduction of samples (Poole, 1957). The main tube narrows at the base to

a rubber connection with a second tube 0.5 cms diameter, 15 cms high, and graduated in mm. The upper edge of the outlet stopcock at the base is zero on the scale. Spring clips A and C are precautionary measures. The plumb line is used to ensure that the two tubes are vertical and exactly in line.

Operation. Air free water fills the tubes to the base of the conical funnel at the top, clip C is closed. The introduction of the sample (fig. 30b, inset), which does not exceed 4.5 gms (Poole et al, 1951), is done from a small corked sample tube, three quarters filled with water, as shown. In this way the sand is thoroughly wetted and all of it starts to settle approximately simultaneously. Two operators are needed at this stage, the second to start the stopwatch. Height readings are taken at time intervals shown on table 17, column 1, and recorded in column 4 (see below). When the material has stopped settling it is run into the small intoductory tube and dried in the oven. The Emery Tube is topped up with water and a further analysis performed. The temperature is 20°C ± 1 , it is checked from time to time.

The Sieves. (fig. 31)

A column of 8" diameter sieves, shaken for 20 minutes in the automatic shaking machine which has a half inch vertical vibration and a varying tilt, is used for obtaining particle size data of coarse material. There is a lid at the top and a pan at the base. The material in each sieve is weighed and recorded on table 18, column 4; the list of sieves is shown in column 1 with maximum B.S. Mesh Tolerances (see below).

The Wet Sieving Apparatus. (fig. 32).

This consists of a seventeen litre cylindrical polythene funnel with a tap at the base and a rim at the top to fit the 8" sieve frames with a sheet of Bolting Silk held tightly between them. The silk has a mesh diameter 0.062 mm when dry, but this appears to decrease slightly when wet. Thus the coarse residue is finally sieved (dry) through a metal sieve (M 240), and the finer material here added to the bulk of the fine suspension (this is part of the "wet sieving process"). Several pieces of silk are used and samples are processed in quick succession. The silk has a longer life than the metal sieves. The final coarse residue is stored, the bulk fine suspension in the funnel is run into a large evaporating basin and dried over a steam bath; when dry it is gently pulverised and stored. The funnel is washed between processes.

Sample Splitters for Sand Material. (fig. 33 a,b,c)

Conical Splitter. This is of Bristol Board with Transpasene to prevent grains from adhering to the cone or the trays. Fine sand is recovered with a fine camel - haired brush.

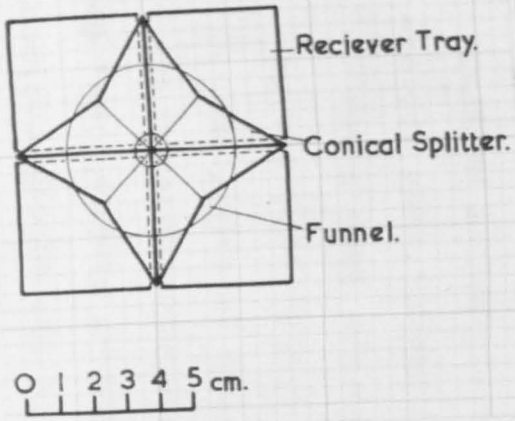
Glass Splitter. This has been described by Smith and Kennard (1961). Material larger than 1 mm needs to be removed with a sieve (M 18) before splitting. Compressed air is used to clean the apparatus after use.

Graduated Litre Funnels. (fig. 34)

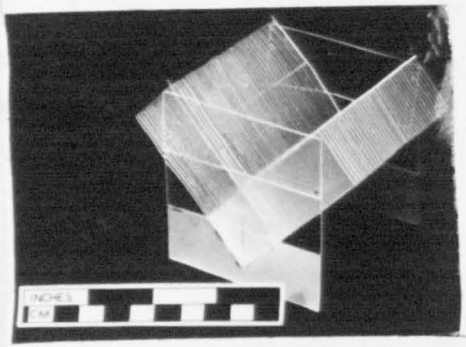
These are used to overcome the problem of trans-ferring a representative portion of liquid suspensions by pouring them from one container to another

N.B. The Drying Oven and the Stirrer are also shown (figs. 35,36).

a. Use of the Conical Splitter.



b. Plan View of the Conical Splitter.



c. Glass Splitten (Smith and Kennard, 1961)

Figure 33. The Splitters.

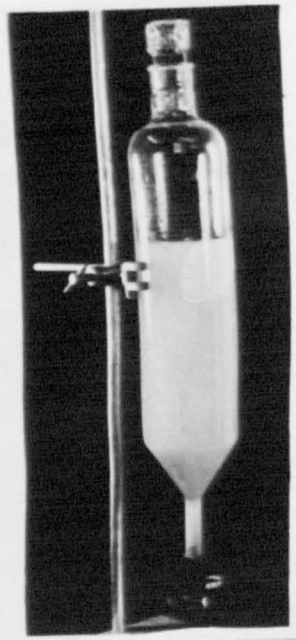
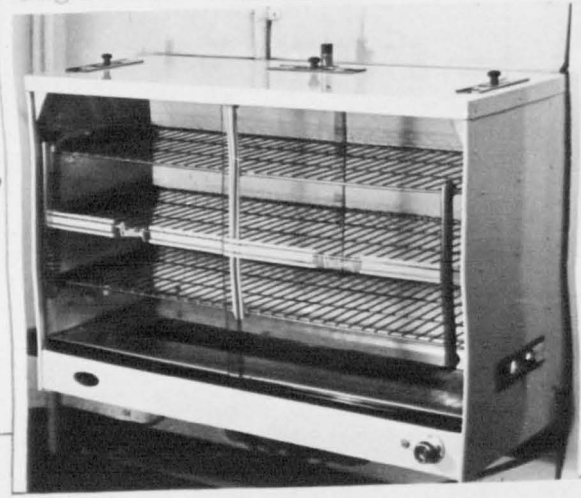


Figure 34. A Graduated Litre Funnel.

Figure 35. The Oven.



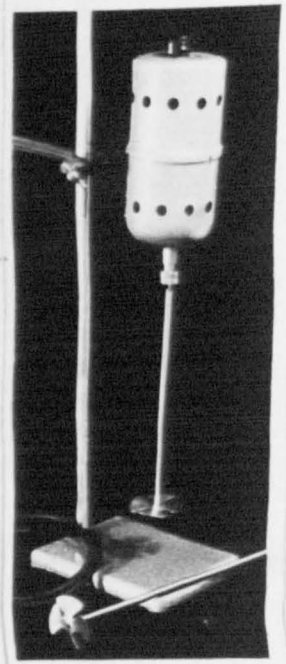


Figure 36. The Stirrer.

Chapter 10. Scheme of Analyses and Procedure.

Particle Size Scales.

Most Windermere material is divided into two separate fractions before analysis. Except in the case of the preliminary study (Chapter 8), Sieve Mesh 240 (mesh diameter 0.064 mm)is used. This is therefore a convenient division between the "Sand Grade" and the "Silt Grade". Wentworth's division (1922) between "silt" and "very fine sand" is 1/16 or 0.0625 mm. Wentworth (1933) suggests that this arbitrary division occurs near a critical change in the aqueous sedimentation of discrete particles (upper limit of Stokes' law, Chapter 6). Within the fine fraction the division between the "Silt Grade" and the "Clay Grade" is taken as 0.002 mm; Wentworth, 1/512 or 0.00195 mm. Grim (1953, p.1) claims that the "clay minerals" rarely occur larger than this.

N.B. These grades do not correspond, even approximately, to the three "fundamental populations of natural sediment particles"postulated by Spencer (1963) which are referred to in greater detail later (Part III).

Certain Late Glacial deposits and beach sands contain particles larger than 2.0 mm (Wentworth's "Pebble Grade"). A summary of the grade scale is shown on table 11.

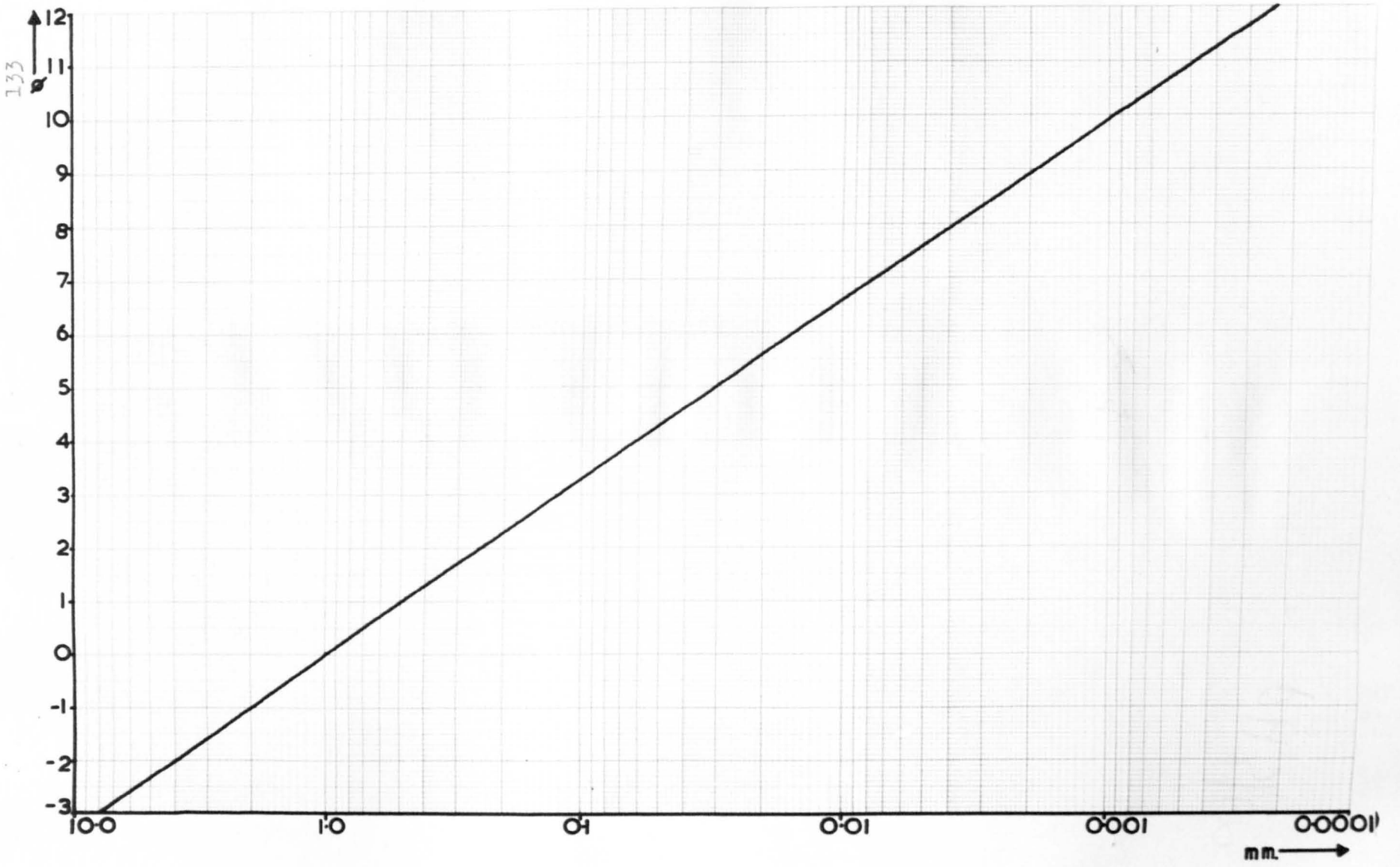
Krumbein's (1936) phi (ϕ) scale is logarithmic with arithmetic intervals corresponding to Wentworth's geometric diameter scale. $\phi = -\log_2 d$ (d is diameter in mm).
It is used here for plotting frequency distribution curves of particle size. Diameter values are converted to phi values for plotting the data. A conversion chart of mm to phi is shown on figure 37.

Table 11. Grade Scale.

Terminology	Size Limits
"Pebbles"	>2.0 mm
"Sand"	0.064 - 2.0 mm
"Silt"	0.002 - 0.064 mm
"Clay"	<0.002 mm

Figure 37. Conversion Chart of Millimetres and Phi.

(A larger and more accurate chart is used in the actual work)



Analyses.

General Scheme.

The full scheme was drawn up as follows:

a. Particle Size Analyses (fine fraction dispersed) of organic samples (ooze and gyttja) before ignition.

b. Settling Rate Analyses (fine fraction undispersed) of organic samples (ooze and gyttja) before ignition.

c. Particle Size Analyses (fine fraction dispersed) of organic samples after ignition and non organic samples.

d. Settling Rate Analyses (fine fraction undispersed) of organic samples after ignition and non organic samples.

Procedure - Flow Sheet (fig. 38)

Quartering by Hand (fig. 39)

The wet sample is placed on a large watch glass and thoroughly mixed. A knife is used to split it into four quarters. Two opposite quarters are combined and used as the main sub-sample (pH, c and d mechanical analyses, mineral, and textural analyses). The other two quarters are requartered and used as shown on figures 38 and 39.

Determination of "Sand Grade Percentage".

Organic Matter Present. The appropriate quarter is dried, weighed, and wet sieved. The fine material is discarded and the coarse material dried and weighed and converted to a percentage of the weight of the whole sample.

Organic Matter Absent. The portion of the main subsample which was ignited was wet sieved. The fine material was retained and the coarse material weighed and converted to a percentage, and retained.

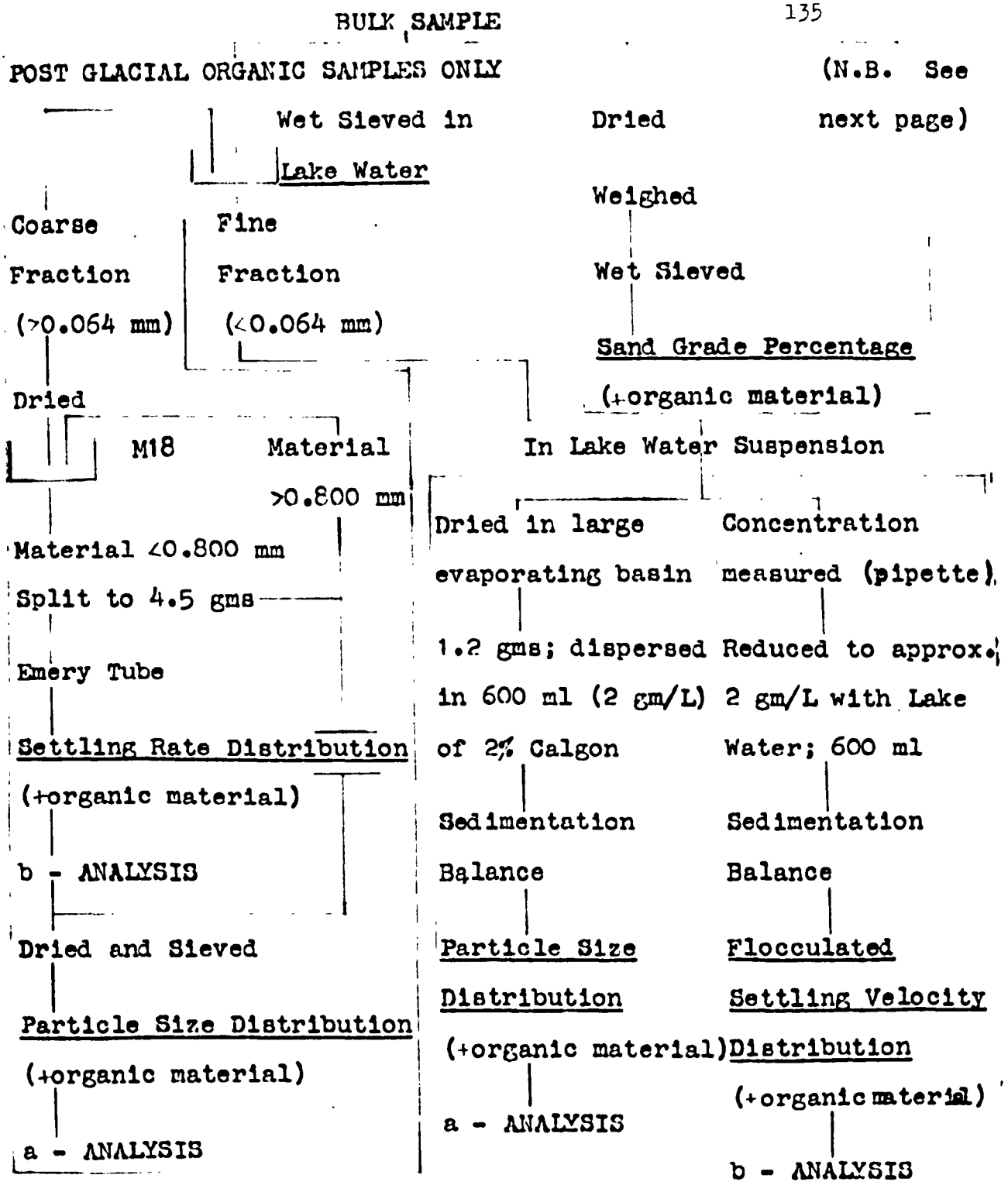


Figure 38. Mechanical Analyses - Full Flow Sheet.

N.B. This is the first half of the diagram, showing the mechanical analyses before removal of organic material; the more important analyses are shown on the next page.

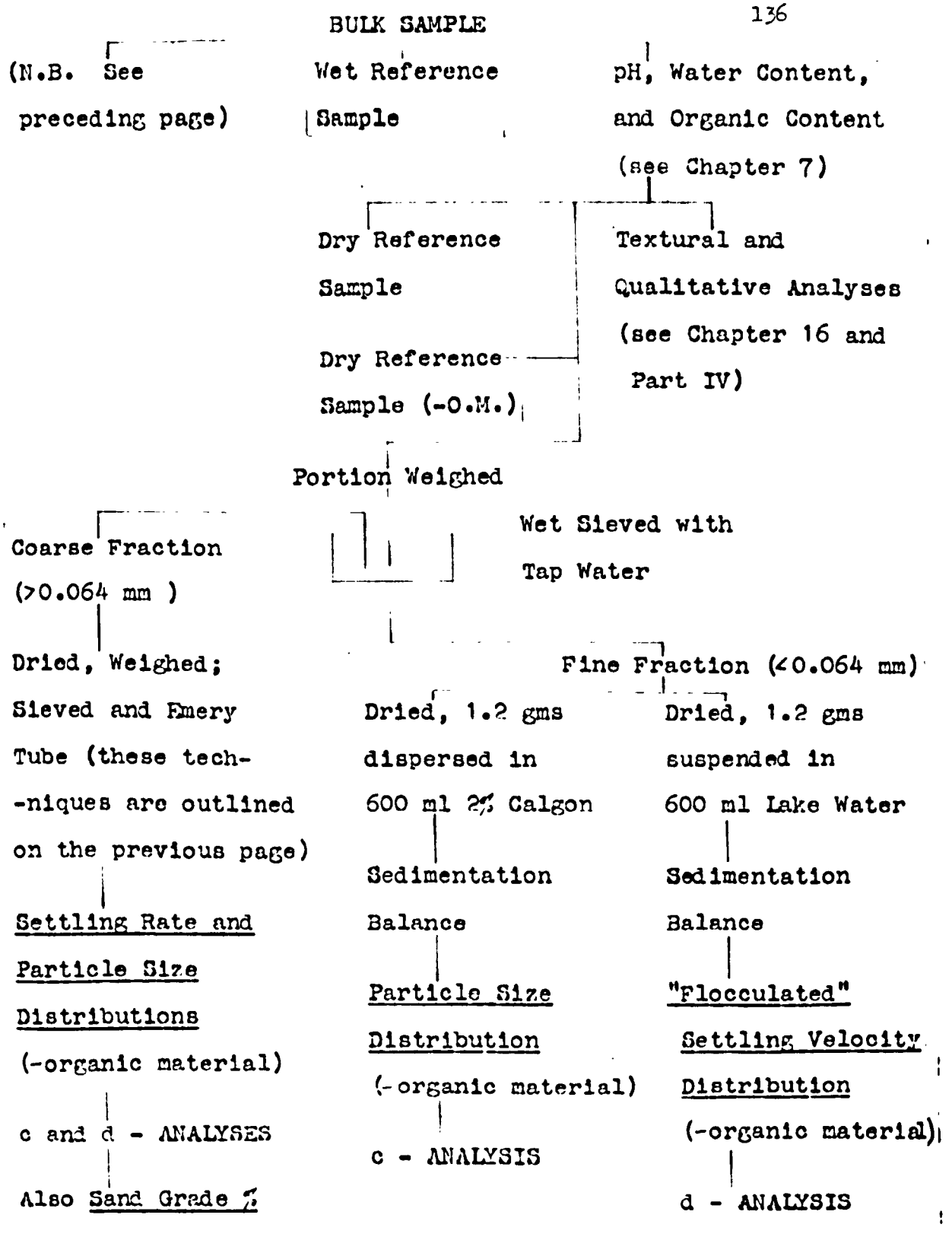
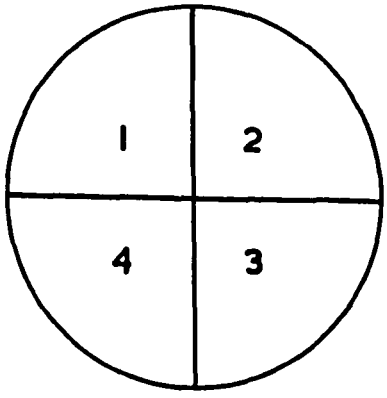


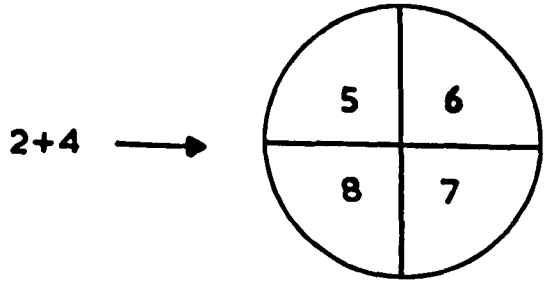
Figure 38 continued. Mechanical Analyses - Full Flow Sheet.

N.B. This is the more important second half of the diagram, showing the mechanical analyses after removal of organic material; the others are on the previous page.



1 + 3 combined - Main Subsample (pH etc.; fig. 38)

2 + 4 combined and requartered



5 + 7 combined - a and b Analyses

6 - Wet Reference Sample (fig. 38)

8 - Sand Grade Percentage (+ Organic Matter)

Figure 39. Scheme for Quartering by Hand.

Preparation of Suspensions for Sedimentation Balance.

Dry fine powder, pulverised in a mortar after drying, was used for preparing suspensions for the a, c, and d analyses. 1.2 gms were weighed in a small beaker and left soaking in the appropriate liquid medium. A stiff brush was used to complete disaggregation and 600 ml of the appropriate suspension made up in the special litre funnels, giving a concentration of 2 gms/L. Dispersal is completed in the cases of a and c analyses by boiling the newly made calgon suspensions in 2 litre flasks at reduced pressure for 45 minutes (Krumbein and Pettijohn, 1938). They are cooled and remade up to 600 ml with distilled water in the litre funnels. They are then stirred for 30 minutes in litre beakers and are ready for analysis within 48 hours to keep evaporation to a minimum.

A different technique is involved for analysis b because it was intended to reproduce flocculation and settling conditions in the lake as accurately as possible. Thus the material is not dried at any stage before analysis. The concentration that passed through the wet sieve is reduced to approximately 2 gms/L and measured accurately.

N.B. 2% Calgon is used as the dispersing agent; it is brought to a pH of 8.3 with phenolphthalein and sodium carbonate. Lake water is used for the settling rate analyses; it was collected from near the water surface in the middle of the lake and brought the laboratory in polythene containers.

Analyses of Coarse Material.

The wet sieved residue is prepared for the Emery Tube and analysed (4.5 gms; fig. 38). It is added to the rest of the coarse material and sieved to give the particle size analysis.

Three convenient Reference Subsamples are retained.

Chapter 11. Calculations.

General Scheme. (Statistical definitions, Chapter 13

The mechanical analyses performed in this study are expressed as individual series of simple data. Interpret-ations of the results are made from these. The three techniques Sedimentation Balance, Emery Tube, and sieves furnish different sets of results for each sample. It is a comparatively simple process to calculate this individual series of data for each sample and it is this which is outlined in some detail in Chapters 11 and 13. Chapter 12 is devoted to outlining tests of accuracy and reproducibility of the first phase calculations shown in Chapter 11. This first phase consists of calculating the Cumulative Percentage Oversize Frequency Distribution data at a series of grades and plotting the cumulative curves. These are always plotted on simple arithmetic paper (% oversize vs ϕ or $\log_{10} v$). Logarithmic probability paper was not used because the first purpose of the curves is to provide data, not specifically to study departures from log normality; this is considered later. This is done first for the coarse and fine analyses of each sample separately; then they are combined in the correct proportions on a combined curve. Specific ordinates taken off the cumulative curves, both simple and combined, are used to give the statistical data mentioned by Pettijohn (1957). This second phase of calculation is outlined in Chapter 13 and errors in the graphical methods used are considered.

N.B. The data used to illustrate all these calculations are hypothetical. It is emphasised that the hypothetical Sediment-ation Balance results are the same for settling rate and particle

size; thus any errors here are due to the methods used. In contrast, the hypothetical sieve and Emery Tube results are different for the coarse material illustrations.

Calculations leading to Cumulative Frequency Data.

Sedimentation Balance Results.

Calculation of w after time t.

A series of weight percentages p, settled out of suspension in time t, have been calculated (table 9, column 4). These are plotted on arithmetic graph paper against lnt with the appropriate lnt ordinates emphasised and duplicated for convenience (fig. 40). The weight percentage oversize w has been shown to be $p - \frac{dp}{d\ln t}$ (Chapter 6). Bostock (cited in Cohen, 1959) has outlined a method for the rapid calculation of w (fig. 40). The tangent of the curve p vs lnt is drawn at a convenient value of lnt, say $\ln t_1$ (in this case 9), for which the percentage weight deposited is p_1. Then the intercept (y_1) made by this tangent on the ordinate at $\ln t_1 - 1$ (in this case 8) is equal to w_1 the weight percentage oversize at time t_1. The proof is as follows: The slope of the tangent at $\ln t_1$ is equal to $\tan \alpha = \frac{y_2 - y_1}{2} = (dp/d\ln t)_1$, where y_2 is the intercept of the tangent on the ordinate at $\ln t_1 \pm 1$ (in this case 10) and p_1 is halfway between y_1 and y_2.

Thus $p_1 = \frac{y_2 + y_1}{2}$. Subtracting, $p_1 - (dp/d\ln t)_1 = y_1$

and therefore $w_1 = y_1$. This is general so that y_1 is equal to w at any time t. Thus readings of y_1 are noted for the values of lnt as shown in table 12, column 1, and are listed as weight percentages oversize at time t in a cumulative series in column 8.

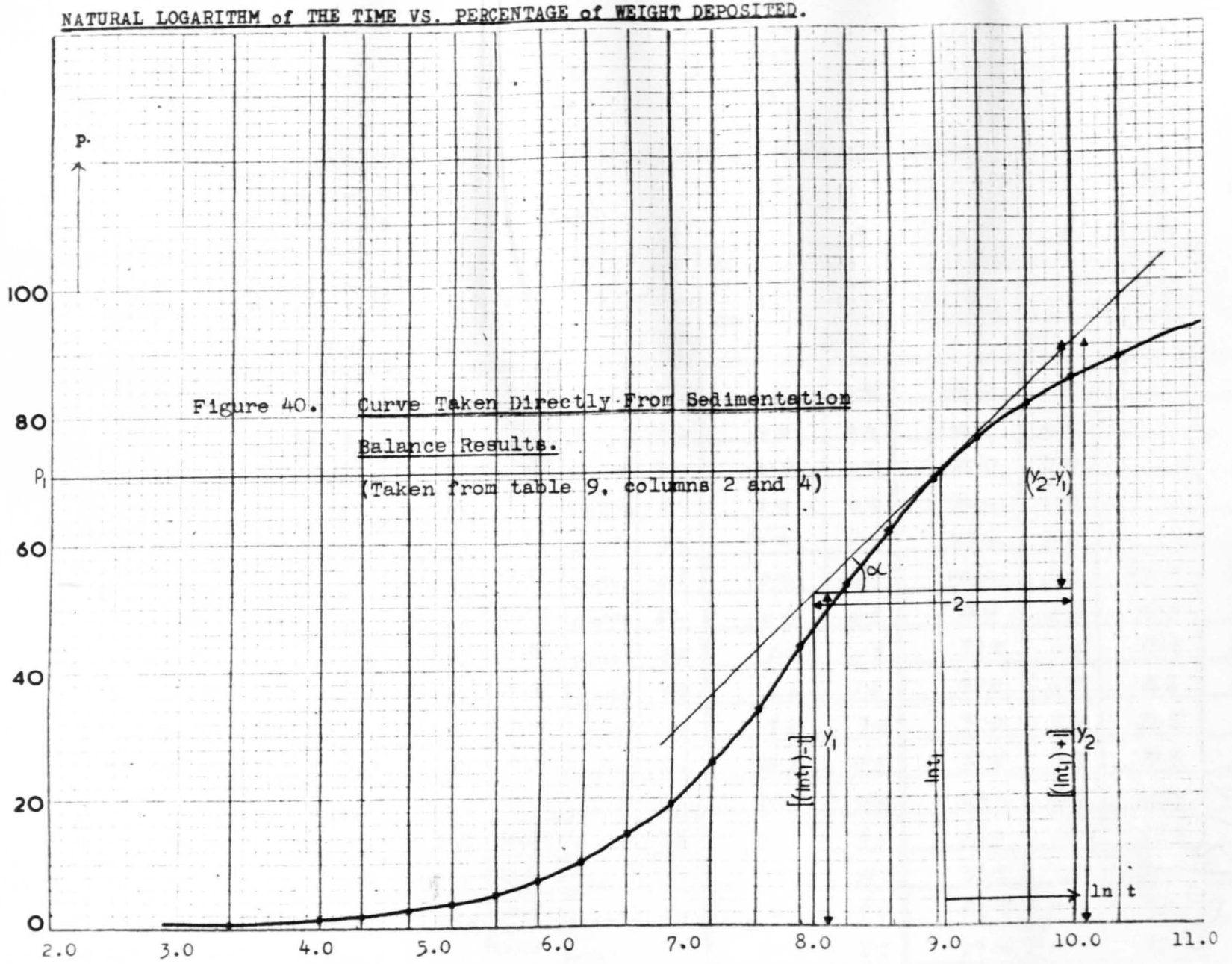


Figure 40. Curve Taken Directly From Sedimentation Balance Results.

(Taken from table 9, columns 2 and 4)

Table 12. PARTICLE SIZE AND SEDIMENTATION RATE ANALYSES - SEDIMENTATION BALANCE

Sand Grade % : 15·0

Fine Fraction % : 85·0 % = 0·850

1	2	3	4	5	6	7	8	9	10	11	12	13
ln t (t in secs)	t (secs)	Velocity, V; $\frac{ho}{t}$ (cms/sec) $L_o = 25·3$	Log_{10} V (Table 13a)	$\sqrt{t}$	diameters, d. c = 0·558		Wt; % oversize of Fine Fraction		% undersize of Fine Fraction - CUMULATIVE	Wt; % oversize of Total Sample		% undersize of Total Sample - CUMULATIVE
					mm.	ϕ (Table 13b)	CUMULATIVE	SIMPLE SIZE		SIMPLE SIZE	CUMULATIVE	
3.0	20.09	1·26	0·10	4.482	0·1250	3·0	0·0	0·0	100·0	0·0		
3.5	33.11	0·76	-0·12	5.754	0·0890	3·4	0·0	0·0	100·0	0·0		
4.0	54.57	0·47	-0·33	7.387	0·0775	3·7	0·0	0·0	100·0	0·0		
4.5	89.94 (1m.30)	0·28	-0·55	9.484	0·0580	4·1	0·0	0·0	100·0	0·0		
5.0	148.20 (2m.28)	0·17	-0·77	12.18	0·0475	4·4	0·0	0·0	100·0	0·0		
5.5	244.30 (4m.4)	0·10	-0·99	15.63	0·0360	4·8	0·0	0·0	100·0	0·0	(15·0)	(85·0)
6.0	402.70 (6m.43)	0·063	-1·20	20.07	0·0270	5·2	0·5	0·5	99·5	0·4	15·4	84·6
6.5	666.80 (11m.7)	0·038	-1·42	25.83	0·0220	5·5	1·0	0·5	99·0	0·4	15·8	84·2
7.0	1,096 (18m.16)	0·023	-1·64	33.11	0·0168	5·9	2·0	1·0	98·0	0·8	16·6	83·4
7.5	1,807 (30m.7)	0·014	-1·85	42.51	0·0127	6·3	9·0	7·0	91·0	5·9	22·5	77·5
8.0	2,978 (49m.38)	0·0085	-2·07	54.57	0·0102	6·6	20·5	11·5	79·5	9·8	32·3	67·7
8.5	4,910 (81m.50)	0·0051	-2·29	70.07	0·0078	7·0	35·5	15·0	64·5	12·8	45·1	54·9
9.0	8,071 (134m.31)	0·0032	-2·50	89.84	0·0063	7·3	52·0	16·5	48·0	14·0	59·0	41·0
9.5	13,330 (222m.10)	0·0019	-2·72	115.4	0·0048	7·7	66·5	14·5	33·5	12·3	71·4	28·6
10.0	21,980 (366m.20)	0·0011	-2·94	148.3	0·0037	8·1	75·5	9·0	24·5	7·7	79·1	20·9
10.5	36,220 (603m.40)	0·00069	-3·16	190.4	0·0030	8·4	81·0	5·5	19·0	4·7	83·8	16·2

Percentages undersize and simple size frequencies are listed in columns 9 and 10. It is now necessary to realise t in terms of particle size or settling velocity.

Calculation of Settling Velocity.

The times t in seconds corresponding to lnt are tabulated in table 12, column 2; these are always the same as they are arbitrary. Settling velocity is equal to h_0/t where h_0 is the height of a particular suspension and may vary between 24.0 and 26.0 cms. Thus the settling velocities of corresponding lnt's are calculated and listed in column 3. A rapid method for determining $\log_{10} v$ for the different values of h_0 was devised. v and $\log_{10} v$ were calculated for each of the twenty values of h_0 between 24.0 and 26.5. These $\log_{10} v$ values were tabulated (table 13a) and the appropriate values listed, when h_0 was known for each separate analysis (values of v were generally omitted as unnecessary), in column 4.

Calculations of Particle "Diameters".

$d = C/t^{1/2}$, where $C = \left[\frac{18h\eta_0 \times 100}{(\sigma - \rho)g}\right]^{1/2}$ (Stokes' Law).

Values of $t^{1/2}$ corresponding to lnt are listed in table 12, column 5; these are always the same as they are arbitrary. C is the test constant for the Sedimentation Balance and varies from analysis to analysis according to Stokes' Law. A rapid method for calculating C for each analysis was devised. σ and g are constant ($\sigma = 2.65$ and $g = 981$ cms/sec^2) and vary with the ambient temperature, h_0 varies independantly between 24.0 and 26.0 cms.

Thus $C = c.h_0^{1/2}$, where $c = \left[\frac{18\eta \times 100}{(\sigma - \rho)g}\right]^{1/2}$, and varies with

Table 13a. $\log_{10} v$ Values Corresponding to lnt for Different Values of h_0.

lnt	24.0	24.1	24.2	24.3	24.4	24.5	24.6	24.7	24.8	24.9	25.0	25.1	25.2	25.3
3.0	$\bar{0}$.08	$\bar{0}$.08	$\bar{0}$.08	$\bar{0}$.08	$\bar{0}$.08	$\bar{0}$.09	$\bar{0}$.09	$\bar{0}$.09	$\bar{0}$.09	$\bar{0}$.09	$\bar{0}$.09	$\bar{0}$.10	$\bar{0}$.10	$\bar{0}$.10
3.5	$\bar{0}$.14	$\bar{0}$.14	$\bar{0}$.14	$\bar{0}$.13	$\bar{0}$.13	$\bar{0}$.13	$\bar{0}$.13	$\bar{0}$.13	$\bar{0}$.13	$\bar{0}$.12	$\bar{0}$.12	$\bar{0}$.12	$\bar{0}$.12	$\bar{0}$.12
4.0	$\bar{0}$.36	$\bar{0}$.35	$\bar{0}$.35	$\bar{0}$.35	$\bar{0}$.35	$\bar{0}$.35	$\bar{0}$.35	$\bar{0}$.34	$\bar{0}$.34	$\bar{0}$.34	$\bar{0}$.34	$\bar{0}$.34	$\bar{0}$.34	$\bar{0}$.33
4.5	$\bar{0}$.57	$\bar{0}$.57	$\bar{0}$.57	$\bar{0}$.57	$\bar{0}$.57	$\bar{0}$.56	$\bar{0}$.56	$\bar{0}$.56	$\bar{0}$.56	$\bar{0}$.56	$\bar{0}$.56	$\bar{0}$.55	$\bar{0}$.55	$\bar{0}$.55
5.0	$\bar{0}$.79	$\bar{0}$.79	$\bar{0}$.79	$\bar{0}$.79	$\bar{0}$.78	$\bar{0}$.78	$\bar{0}$.78	$\bar{0}$.78	$\bar{0}$.78	$\bar{0}$.77	$\bar{0}$.77	$\bar{0}$.77	$\bar{0}$.77	$\bar{0}$.77
5.5	$\bar{1}$.01	$\bar{1}$.01	$\bar{1}$.01	$\bar{1}$.00	$\bar{1}$.00	$\bar{1}$.00	$\bar{1}$.00	$\bar{1}$.00	$\bar{0}$.99	$\bar{0}$.99	$\bar{0}$.99	$\bar{0}$.99	$\bar{0}$.99	$\bar{0}$.99
6.0	$\bar{1}$.22	$\bar{1}$.22	$\bar{1}$.22	$\bar{1}$.22	$\bar{1}$.22	$\bar{1}$.22	$\bar{1}$.21	$\bar{1}$.21	$\bar{1}$.21	$\bar{1}$.21	$\bar{1}$.21	$\bar{1}$.21	$\bar{1}$.20	$\bar{1}$.20
6.5	$\bar{1}$.44	$\bar{1}$.44	$\bar{1}$.44	$\bar{1}$.44	$\bar{1}$.43	$\bar{1}$.43	$\bar{1}$.43	$\bar{1}$.43	$\bar{1}$.43	$\bar{1}$.43	$\bar{1}$.43	$\bar{1}$.42	$\bar{1}$.42	$\bar{1}$.42
7.0	$\bar{1}$.66	$\bar{1}$.66	$\bar{1}$.66	$\bar{1}$.65	$\bar{1}$.65	$\bar{1}$.65	$\bar{1}$.65	$\bar{1}$.65	$\bar{1}$.65	$\bar{1}$.64	$\bar{1}$.64	$\bar{1}$.64	$\bar{1}$.64	$\bar{1}$.64
7.5	$\bar{1}$.88	$\bar{1}$.87	$\bar{1}$.87	$\bar{1}$.87	$\bar{1}$.87	$\bar{1}$.87	$\bar{1}$.87	$\bar{1}$.86	$\bar{1}$.86	$\bar{1}$.86	$\bar{1}$.86	$\bar{1}$.86	$\bar{1}$.86	$\bar{1}$.85
8.0	$\bar{2}$.09	$\bar{2}$.09	$\bar{2}$.09	$\bar{2}$.09	$\bar{2}$.09	$\bar{2}$.08	$\bar{2}$.08	$\bar{2}$.08	$\bar{2}$.08	$\bar{2}$.08	$\bar{2}$.08	$\bar{2}$.07	$\bar{2}$.07	$\bar{2}$.07
8.5	$\bar{2}$.31	$\bar{2}$.31	$\bar{2}$.31	$\bar{2}$.31	$\bar{2}$.30	$\bar{2}$.30	$\bar{2}$.30	$\bar{2}$.30	$\bar{2}$.30	$\bar{2}$.29	$\bar{2}$.29	$\bar{2}$.29	$\bar{2}$.29	$\bar{2}$.29
9.0	$\bar{2}$.53	$\bar{2}$.53	$\bar{2}$.52	$\bar{2}$.52	$\bar{2}$.52	$\bar{2}$.52	$\bar{2}$.52	$\bar{2}$.52	$\bar{2}$.51	$\bar{2}$.51	$\bar{2}$.51	$\bar{2}$.51	$\bar{2}$.51	$\bar{2}$.50
9.5	$\bar{2}$.74	$\bar{2}$.74	$\bar{2}$.74	$\bar{2}$.74	$\bar{2}$.74	$\bar{2}$.74	$\bar{2}$.73	$\bar{2}$.73	$\bar{2}$.73	$\bar{2}$.73	$\bar{2}$.73	$\bar{2}$.73	$\bar{2}$.72	$\bar{2}$.72
10.0	$\bar{2}$.96	$\bar{2}$.96	$\bar{2}$.96	$\bar{2}$.96	$\bar{2}$.96	$\bar{2}$.95	$\bar{2}$.95	$\bar{2}$.95	$\bar{2}$.95	$\bar{2}$.95	$\bar{2}$.95	$\bar{2}$.94	$\bar{2}$.94	$\bar{2}$.94
10.5	3.18	3.18	3.17	3.17	3.17	3.17	3.17	3.17	3.16	3.16	3.16	3.16	3.16	3.16

N.B. In this table, $\bar{2}$.08, for instance, means "minus 2.08".

Table 13a (continued.)

lnt	25.4	25.5	25.6	25.7	25.8	25.9	26.0	26.1	26.2	26.3	26.4	26.5
3.0	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12
3.5	$\bar{0}$.12	$\bar{0}$.11	$\bar{0}$.11	$\bar{0}$.11	$\bar{0}$.11	$\bar{0}$.11	$\bar{0}$.11	$\bar{0}$.10	$\bar{0}$.10	$\bar{0}$.10	$\bar{0}$.10	$\bar{0}$.10
4.0	$\bar{0}$.33	$\bar{0}$.33	$\bar{0}$.33	$\bar{0}$.33	$\bar{0}$.32	$\bar{0}$.32	$\bar{0}$.32	$\bar{0}$.32	$\bar{0}$.32	$\bar{0}$.32	$\bar{0}$.31	$\bar{0}$.31
4.5	$\bar{0}$.55	$\bar{0}$.55	$\bar{0}$.55	$\bar{0}$.54	$\bar{0}$.54	$\bar{0}$.54	$\bar{0}$.54	$\bar{0}$.54	$\bar{0}$.54	$\bar{0}$.53	$\bar{0}$.53	$\bar{0}$.53
5.0	$\bar{0}$.77	$\bar{0}$.76	$\bar{0}$.76	$\bar{0}$.76	$\bar{0}$.76	$\bar{0}$.76	$\bar{0}$.76	$\bar{0}$.75	$\bar{0}$.75	$\bar{0}$.75	$\bar{0}$.75	$\bar{0}$.75
5.5	$\bar{0}$.98	$\bar{0}$.98	$\bar{0}$.98	$\bar{0}$.98	$\bar{0}$.98	$\bar{0}$.98	$\bar{0}$.97	$\bar{0}$.97	$\bar{0}$.97	$\bar{0}$.97	$\bar{0}$.97	$\bar{0}$.97
6.0	$\bar{1}$.20	$\bar{1}$.20	$\bar{1}$.20	$\bar{1}$.20	$\bar{1}$.19	$\bar{1}$.19	$\bar{1}$.19	$\bar{1}$.19	$\bar{1}$.19	$\bar{1}$.18	$\bar{1}$.18	$\bar{1}$.18
6.5	$\bar{1}$.42	$\bar{1}$.42	$\bar{1}$.42	$\bar{1}$.41	$\bar{1}$.41	$\bar{1}$.41	$\bar{1}$.41	$\bar{1}$.41	$\bar{1}$.41	$\bar{1}$.40	$\bar{1}$.40	$\bar{1}$.40
7.0	$\bar{1}$.64	$\bar{1}$.63	$\bar{1}$.63	$\bar{1}$.63	$\bar{1}$.63	$\bar{1}$.63	$\bar{1}$.62	$\bar{1}$.62	$\bar{1}$.62	$\bar{1}$.62	$\bar{1}$.62	$\bar{1}$.62
7.5	$\bar{1}$.85	$\bar{1}$.85	$\bar{1}$.85	$\bar{1}$.85	$\bar{1}$.85	$\bar{1}$.84	$\bar{1}$.84	$\bar{1}$.84	$\bar{1}$.84	$\bar{1}$.84	$\bar{1}$.83	$\bar{1}$.83
8.0	$\bar{2}$.07	$\bar{2}$.07	$\bar{2}$.07	$\bar{2}$.06	$\bar{2}$.06	$\bar{2}$.06	$\bar{2}$.06	$\bar{2}$.06	$\bar{2}$.06	$\bar{2}$.05	$\bar{2}$.05	$\bar{2}$.05
8.5	$\bar{2}$.29	$\bar{2}$.28	$\bar{2}$.28	$\bar{2}$.28	$\bar{2}$.28	$\bar{2}$.28	$\bar{2}$.28	$\bar{2}$.27	$\bar{2}$.27	$\bar{2}$.27	$\bar{2}$.27	$\bar{2}$.27
9.0	$\bar{2}$.50	$\bar{2}$.50	$\bar{2}$.50	$\bar{2}$.50	$\bar{2}$.50	$\bar{2}$.50	$\bar{2}$.49	$\bar{2}$.49	$\bar{2}$.49	$\bar{2}$.49	$\bar{2}$.49	$\bar{2}$.48
9.5	$\bar{2}$.72	$\bar{2}$.72	$\bar{2}$.72	$\bar{2}$.72	$\bar{2}$.71	$\bar{2}$.71	$\bar{2}$.71	$\bar{2}$.71	$\bar{2}$.71	$\bar{2}$.71	$\bar{2}$.70	$\bar{2}$.70
10.0	$\bar{2}$.94	$\bar{2}$.94	$\bar{2}$.94	$\bar{2}$.93	$\bar{2}$.93	$\bar{2}$.93	$\bar{2}$.93	$\bar{2}$.93	$\bar{2}$.93	$\bar{2}$.92	$\bar{2}$.92	$\bar{2}$.92
10.5	$\bar{3}$.15	$\bar{3}$.15	$\bar{3}$.15	$\bar{3}$.15	$\bar{3}$.15	$\bar{3}$.15	$\bar{3}$.14	$\bar{3}$.14	$\bar{3}$.14	$\bar{3}$.14	$\bar{3}$.14	$\bar{3}$.14

N.B. In this table, $\bar{1}$.84, for instance, means "minus 1.84".

Table 13b. ø Values Corresponding to Int for Different Values of C.

Int	ø	C	ø	C	ø	C	ø	C
3.0	3.1	.520 - .543	3.0	.544 - .581	2.9	.582 - .610		
3.5	3.5	.520 - .527	3.4	.528 - .565	3.3	.566 - .604	3.2	.605 - .610
4.0	3.8	.520 - .550	3.7	.551 - .588	3.6	.589 - .610		
4.5	4.2	.520 - .534	4.1	.535 - .572	4.0	.573 - .610		
5.0	4.5	.520 - .558	4.4	.559 - .597	4.3	.598 - .610		
5.5	4.9	.520 - .543	4.8	.544 - .582	4.7	.583 - .610		
6.0	5.3	.520 - .528	5.2	.529 - .566	5.1	.567 - .605	5.0	.606 - .610
6.5	5.6	.520 - .551	5.5	.552 - .589	5.4	.590 - .610		
7.0	6.0	.520 - .536	5.9	.537 - .574	5.8	.575 - .610		
7.5	6.4	.520 - .523	6.3	.524 - .561	6.2	.562 - .599	6.1	.600 - .610
8.0	6.7	.520 - .543	6.6	.544 - .581	6.5	.582 - .610		
8.5	7.1	.520 - .529	7.0	.530 - .567	6.9	.568 - .606	6.8	.607 - .61
9.0	7.4	.520 - .547	7.3	.548 - .586	7.2	.587 - .610		
9.5	7.8	.520 - .542	7.7	.543 - .581	7.6	.582 - .610		
10.0	8.2	.520 - .523	8.1	.524 - .561	8.0	.562 - .600	7.9	.601 - .610
10.5	8.5	.520 - .539	8.4	.540 - .578	8.3	.579 - .610		

ambient temperature only.

Calculations of Liquid Viscosity. Lake Water and 2% Calgon solution were analysed for viscosity at temperatures between 15°and 25°C in the Ostwald Viscometer (fig. 41) borrowed from the Physics Dept. U.C. The time taken for the liquid surface to fall between two marks is used as the basis for viscosity measurement according to the equation $T \propto \upsilon \propto \eta/\rho$, where T is the relevant time of fall, υ is the kinematic viscosity. Thus $T = K\eta/\rho$ or $K = \rho T/\eta$, where K is the calibration constant of the viscometer. This was calculated using the data for distilled water (table 14) by plotting density and viscosity against temperature (fig. 42 a and b). The viscometer was supported firmly and vertically in a water bath which was heated and cooled using a gentle bunsen flame and ice respectively and made homogeneous by stirring continuously. The readings were taken just beside the viscometer (average of three), they were considered satisfactory when within 0.5 secs of each other. K(distilled water) $= \rho T/\eta = \underline{3032.86}$ where T (average) = 30.93. Temperature is 19.5°C, therefore $\rho = 0.9981$ (fig. 42a) and $\eta = 0.01018$ (fig. 42b).

Viscosity measurements for calgon and lake water are listed in table 15 a and b; they are plotted against temperature in figure 42c.

Calculations of Liquid Density. The liquid specimen was in a cylindrical flask in the controlled water bath. Twadell Hydrometers Nos. 1 and 2 were used; the temperature was taken and the liquid stirred in the flask. No differences were detected for the density of these liquids between 15°and 25°C.; ρ(calgon) = 2.5°Tw. = $\underline{1.0125}$(gms/ml); ρ(lake water) = 0°Tw. = $\underline{1.0}$.

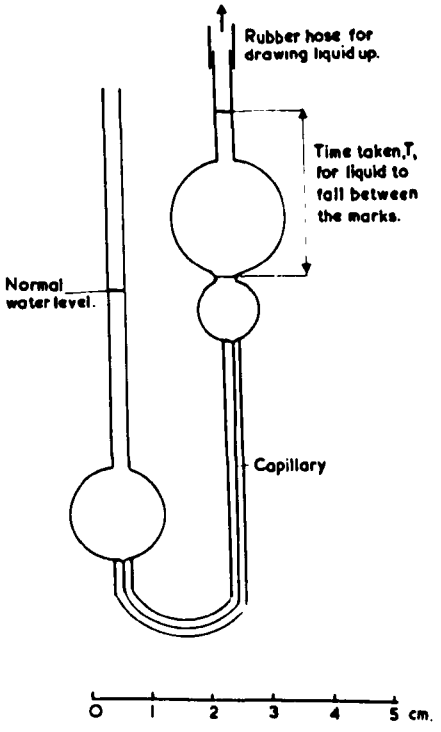


Figure 41. The Ostwald Viscometer.

Table 14. Viscosities and Densities of Distilled Water.

Temperature (°C)	η, Viscosity (Poise)	ρ, Density (gm/ml)
10	0.01311	1.0000
15	0.01143	0.9990
20	0.01006	0.9980
25	0.00893	0.9970

Table 15. Calculation of c.

a. Calgon Solution in the Viscometer.

ρ = 1.0125

Temp. (°C)	T1	T2	T3	T(av.) (secs)	ρ T	$\frac{\rho T}{3032.86} - \eta$
15.7	36.1	35.9	36.1	36.067	36.5178	0.01204
16.6	35.5	35.5	35.4	35.467	35.9103	0.01184
17.2	34.9	35.1	34.9	34.967	35.4041	0.01167
18.3	34.3	34.4	34.2	34.300	34.7287	0.01145
19.4	33.2	33.0	33.4	33.233	33.6484	0.01110
20.6	32.6	32.6	32.5	32.617	33.0247	0.01089
21.4	32.1	31.9	32.1	32.050	32.4506	0.01070
23.0	31.2	31.3	31.2	31.267	31.6578	0.01044
24.4	30.1	30.4	30.3	30.267	30.6453	0.01010
25.1	30.0	29.8	29.8	29.883	30.2565	0.00998

Table 15. b. Lake Water in the Viscometer.

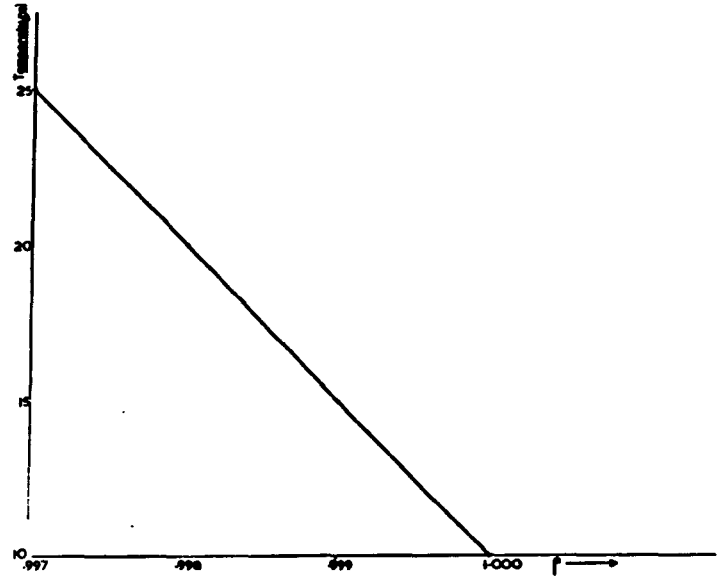
$\rho = 1.0$

Temp. (°C)	T1	T2	T3	T(av.) (secs)	ρT	$\frac{\rho T}{3032.86} - \eta$
15.6	33.4	33.5	33.5	33.517	33.517	0.01 05
16.5	32.8	32.9	33.0	32.933	32.933	0.01 6
17.3	32.1	32.1	32.2	32.167	32.167	0.01061
19.7	30.5	30.5	30.6	30.550	30.550	0.01007
21.4	29.7	29.6	29.6	29.650	29.650	0.00978
22.2	28.9	28.7	28.7	28.783	28.783	0.00949
23.6	28.4	28.3	28.1	28.300	28.300	0.00933
24.1	28.1	28.2	28.3	28.216	28.216	0.00930
24.7	27.8	27.8	27.7	27.783	27.783	0.00916
25.2	27.7	27.7	27.7	27.716	27.716	0.00914

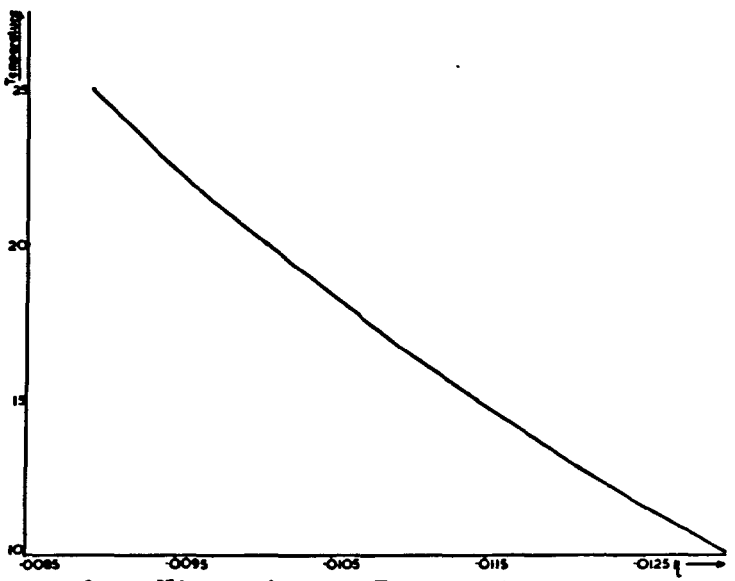
c. Calculations of values of c.

Calgon Solution ($6-\rho$ = 1.6375) Lake Water ($6-\rho$ = 1.6500)

Temp.	Viscosity	c	Temp.	Viscosity	c
15.0	0.01222	0.1170	15.0	0.01118	0.1115
16.0	0.01196	0.1158	16.0	0.01090	0.1101
17.0	0.01172	0.1146	17.0	0.01068	0.1090
18.0	0.01148	0.1134	18.0	0.01045	0.1078
19.0	0.01124	0.1122	19.0	0.01024	0.1067
20.0	0.01100	0.1110	20.0	0.01004	0.1057
21.0	0.01079	0.1099	21.0	0.00984	0.1046
22.0	0.01058	0.1089	22.0	0.00963	0.1034
23.0	0.01038	0.1078	23.0	0.00945	0.1025
24.0	0.01018	0.1068	24.0	0.00928	0.1016
25.0	0.01000	0.1058	25.0	0.00913	0.1007

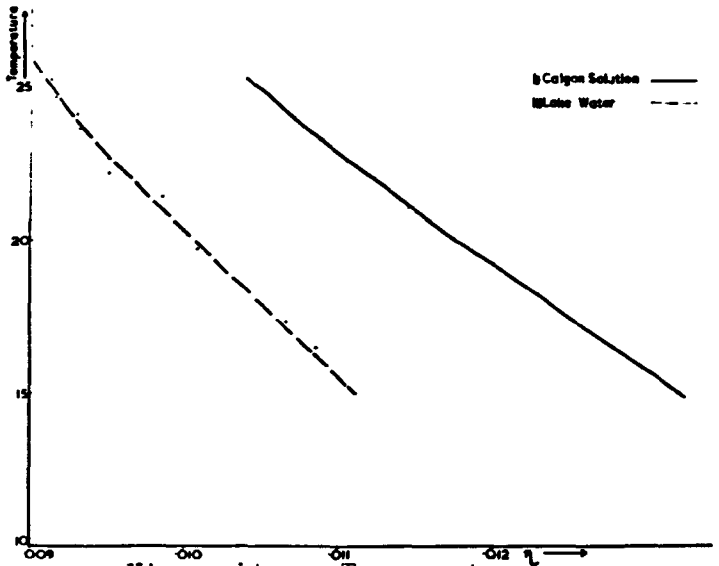


a. Density - Temperature;

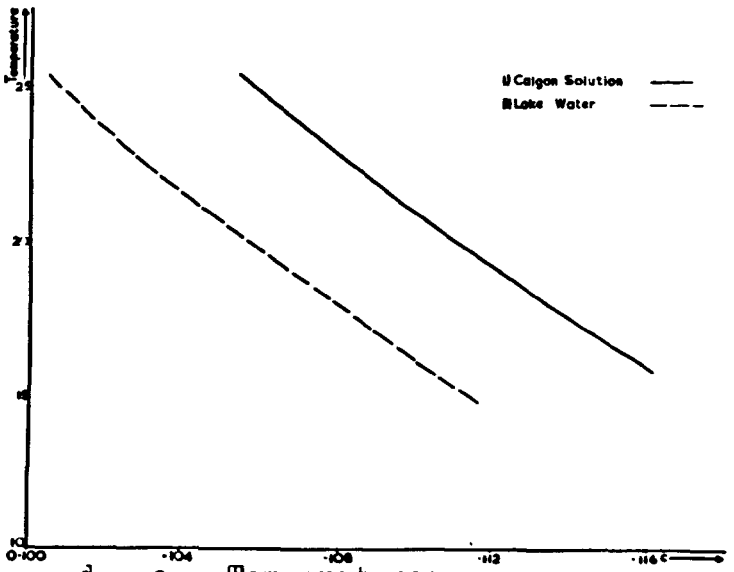


b. Viscosity - Temperature;

Distilled Water (table 14).



c. Viscosity - Temperature;



d. c - Temperature;

Table 15 a, b, c.

Figure 42. Calculation of c.

Calculation of c. Viscosity values between 15° and 25°C are read off figure 42c and liquid densities are known. c is calculated between 15° and 25°C for the two liquid media (table 15c) and plotted against temperature (fig. 42d).

Calculation of C. h_0 values are determined for each analysis and c is read off figure 42d. The test constant C is calculated each time, $c.h_0^{1/2}$.

Calculation of d. C is known for each analysis and is divided by $t^{1/2}$, for the series of lnt values for which the weight percentage oversize is known, to give d in mm.

Rapid Calculation of d in ø. C was found to vary well within the range 0.520 to 0.610. d values for all ninety C values between 0.520 and 0.610 were calculated for the appropriate lnt values; these were converted to ø using figure 37. The ø values were tabulated in table 13b and the appropriate readings from here listed in table 12, column 7, after C was known for each analysis (mm values of d were generally omitted from column 6).

Data Sheet for the Sedimentation Balance. (table 16)

One of these sheets was completed immediately after each analysis. It was not mentioned earlier in this discussion because the terms used had not been explained at that stage.

Summary.

The data sheet (table 16) is completed immediately after each analysis. When the film has been developed the readings are converted to p values (table 9). These are plotted against lnt on the special arithmetic graph paper

Table 16. Sedimentation Balance Data Sheet.

Date: 15th March 1963.

Starting Time: 9.15 a.m.

Temperature (°C): 20.0° ; ∴ c = 0.111. (fig. 42d)

Medium: Distilled Water

η, Viscosity of Medium (poise): 0.0110 (fig. 42c)

ρ, Density of Medium ($^{gm}/_{ml}$): 1.025

Dispersing Agent: Calgon

ho, Height of Suspension (cms): 25.3 ; ∴ $\sqrt{ho}$ = 5.03

σ, Density of Sample ($^{gm}/_{ml}$): 2.65

Concentration of Sample in Suspension ($^{gm}/_{l}$): 2.00

Balance Sensitivity: 2.0

Test No: — (N.B. Hypothetical)

C, Test Constant: $\sqrt{\frac{18h_o \times 10^8}{(\sigma - \rho)g}}$: 0.558

or $c\sqrt{L_o}$.

Results from a separate settling tube

Volume of Suspension: 269.3 ml. (Table 10)

wo, Weight of Sample (gm): 0.539 gms. $\left(\frac{\text{volume} \times \text{conc.}}{1000}\right)$

x : 2.1 cms.

$h_1 = ho + x$: 27.4 cms.

w_1 : 0.386 gms.

t (mins) : 128

∴ % by weight deposited in time t = $\frac{w_1 - (x/h_1)\, wo}{wo - (x/h_1)\, wo} \times 100$

= 69.3.

(fig. 40). Tangents to this curve are drawn at the appropriate values of lnt and the y_1 intercepts on the ordinates (lnt - 1) listed in column 8 (table 12). Log$_{10}$ v or ϕ values are taken off table 13 a and b according to the test values of h_0 and C; these are noted in columns 4 or 7 (table 12) and are opposite the appropriate w values. Simple size and percentages undersize are listed if required in columns 9 and 10.

Settling Rate Distribution Curves of Fine Material. Figure 43 shows the hypothetical examples of percentage oversize (both simple size and cumulative) vs log$_{10}$ v on arithmetic paper. Generally the simple size curve is omitted.

Particle Size Distribution Curves of Fine Material. Figure 44 shows the hypothetical examples of percentage oversize (both simple size and cumulative) vs phi (ϕ) on arithmetic paper. Generally the simple size curve is omitted.

Emery Tube Results.

Accumulating height values are recorded in table 17, column 4. The time intervals are fixed and correspond to values of v and log$_{10}$ v (columns 1, 2, and 3). The height values are converted into percentages of the ultimate reading (in this case, 13.8), these cumulative percentages are plotted against log$_{10}$ v on arithmetic graph paper (fig. 45). The simple size frequencies are calculated when required and listed in column 5. The simple size curve is not generally plotted.

N.B. When there is a proportion of material larger than Sieve Mesh 18 the appropriate adjustments are made to the Emery Tube data.

FINE FRACTION - GRAPH NOS. 3 a & b.

SAMPLE SHEET NO.

VOLUME PERCENTAGE FALLING FASTER THAN V, VS. $\log_{10}$ SETTLING VELOCITY ($\log_{10}$V)

(a) CUMULATIVE FREQUENCY CURVE

(b) SIMPLE FREQUENCY CURVE

(N.B. ALL PERCENTAGES ARE of FINE FRACTION ONLY)

Diameters plotted for a temperature of °C.; assuming a solid density of 2.65 $\frac{gms}{cc.}$

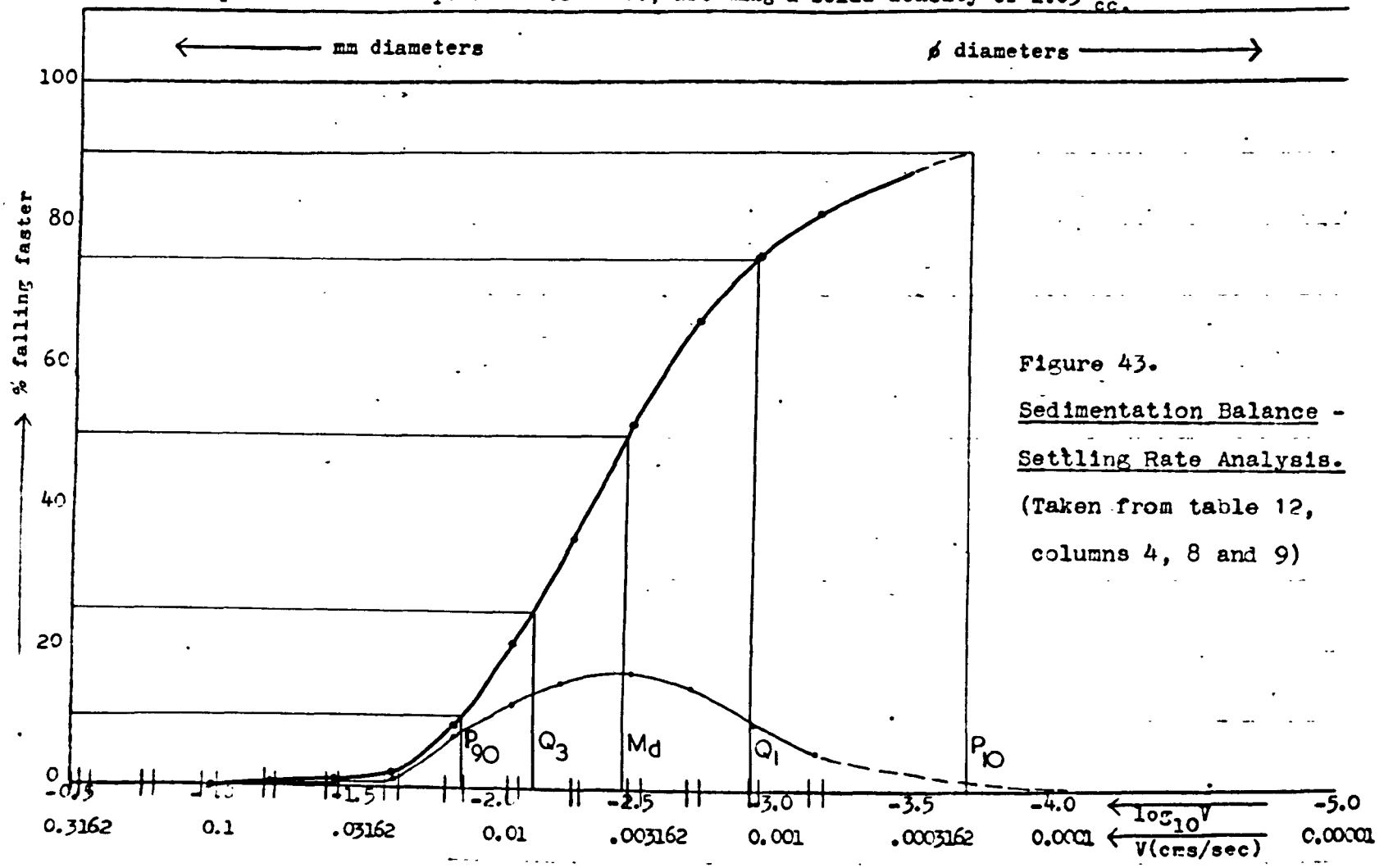


Figure 43.

Sedimentation Balance - Settling Rate Analysis.

(Taken from table 12, columns 4, 8 and 9)

FINE FRACTION - GRAPH NOS. 3 a & b. SAMPLE SHEET NO.

VOLUME PERCENTAGE FALLING FASTER THAN V, VS. $\log_{10}$ SETTLING VELOCITY ($\log_{10}$V)

(a) CUMULATIVE FREQUENCY CURVE

(b) SIMPLE FREQUENCY CURVE

(N.B. ALL PERCENTAGES ARE of FINE FRACTION ONLY)

Diameters plotted for a temperature of °C.; assuming a solid density of 2.65 $\frac{gms}{cc.}$

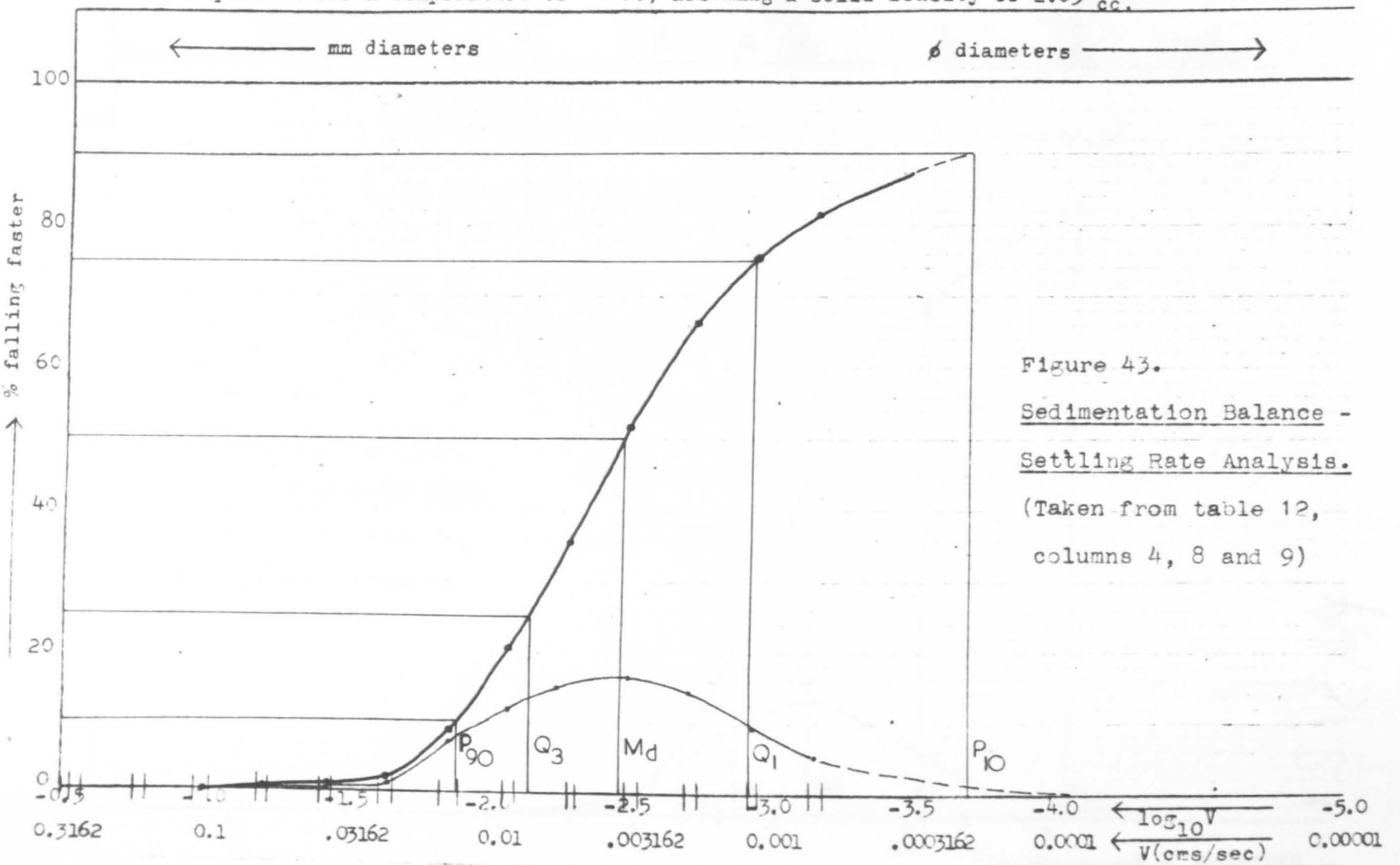


Figure 43.

Sedimentation Balance - Settling Rate Analysis.

(Taken from table 12, columns 4, 8 and 9)

FINE FRACTION - GRAPH NOS. 2 a & b. SAMPLE SHEET NO.

WEIGHT PERCENTAGE OVERSIZE VS PHI DIAMETERS - (a) CUMULATIVE FREQUENCY CURVE

(b) SIMPLE SIZE FREQUENCY CURVE

(N.B. ALL PERCENTAGES ARE of FINE FRACTION ONLY)

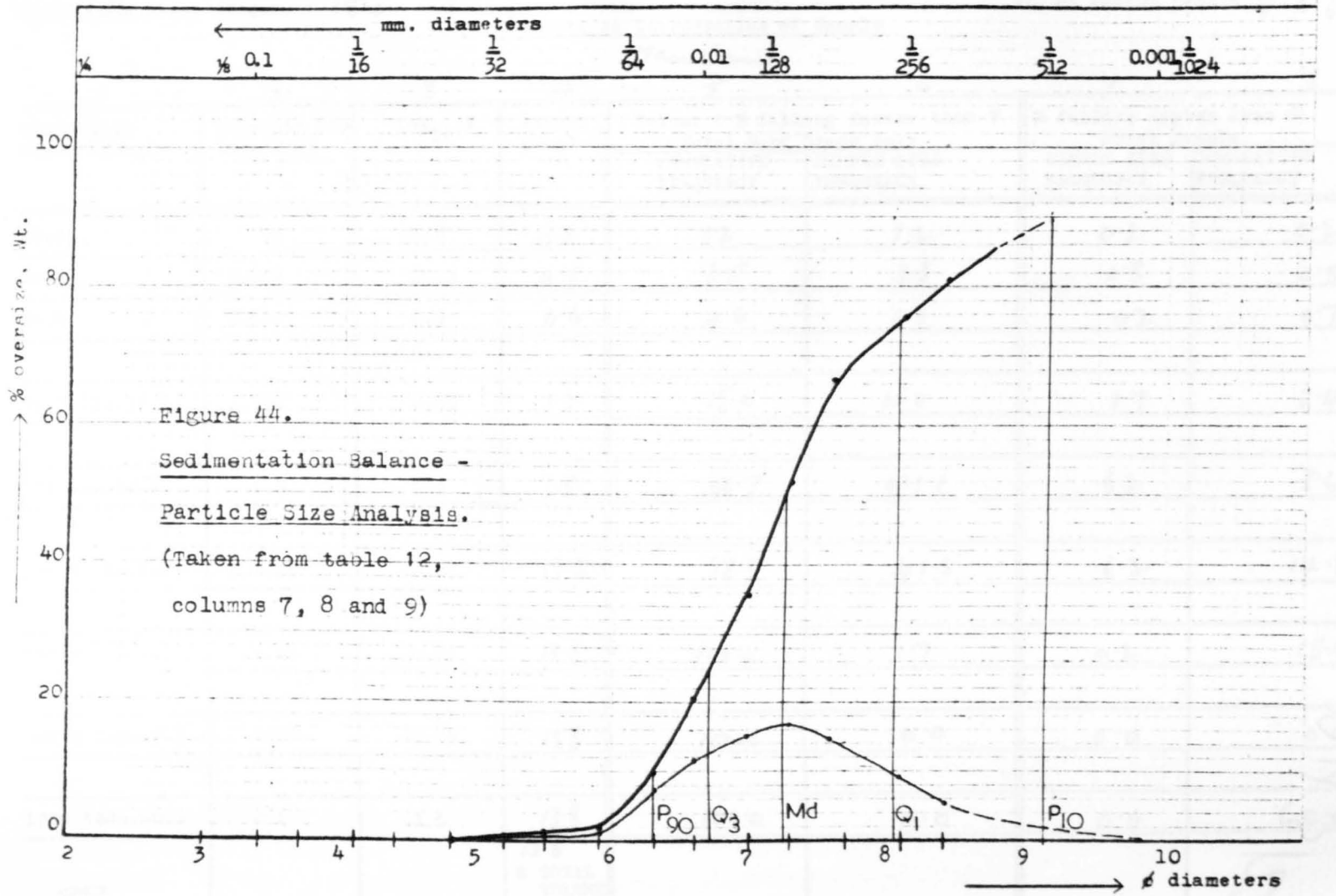


Figure 44.

Sedimentation Balance -

Particle Size Analysis.

(Taken from table 12,

columns 7, 8 and 9)

Table 17. SEDIMENTATION RATE ANALYSIS - EMERY TUBE

Height of Tube : 172 cms; Temperature (°C) : 19°

Date: 22nd March 1963

Sand Grade % (by weight) : 15·0

WT. of Sample (gms): 45 gms.

Comments on Introduction of Sample

Standard.

1	2	3	4	5	6	7	8
Reading No.	Time after Start (secs)	Velocity (V) (cms/sec)	$\log_{10}$ V	Height (cms)	Volume : % falling faster than V Total Sand Grade only		% falling faster than V Total Sample	
					CUMULATIVE FREQUENCY	SIMPLE SIZE FREQUENCY	SIMPLE SIZE FREQUENCY	CUMULATIVE FREQUENCY
1	17.2	10	1.0	0·2	1·2	1·2	0·2	0·2
2	30.6	5.624	0.75	0·5	3·5	2·3	0·3	0·5
3	54.4	3.162	0.5	0·6	4·6	1·1	0·2	0·7
4	96.7 (1m.37.)	1.778	0.25	2·2	15·6	11·0	1·7	2·4
5	172 (2m.52.)	1.0	0.0	7·8	56·7	41·1	6·2	8·6
6	305.9 (5m.6.)	.5624	-0.25	13·6	98·3	41·6	6·2	14·8
7	543.9 (9m.4.)	.3162	-0.50	13·8	100·0	1·7	0·2	15·0
8	967.2 (16m.7.)	.1778	-0.75	13·8	100·0	0·0	0·0	0·0
9	1720 (28m.40.)	0.1	-1.0	13·8	100·0	0·0	0·0	0·0
∞				13·8 ≡ TOTAL VOLUME (100%)				

SAND GRADE - GRAPH NOS. 2 a & b. SAMPLE SHEET NO.

VOLUME PERCENTAGE FALLING FASTER THAN V, VS. $\log_{10}$ SETTLING VELOCITY ($\log_{10}$V)

(a) CUMULATIVE FREQUENCY CURVE

(b) SIMPLE FREQUENCY CURVE

(N.B. ALL PERCENTAGES ARE of SAND GRADE ONLY)

Diameters plotted for a temperature of °C.; assuming a solid density of 2.65 $\frac{gms}{cc.}$

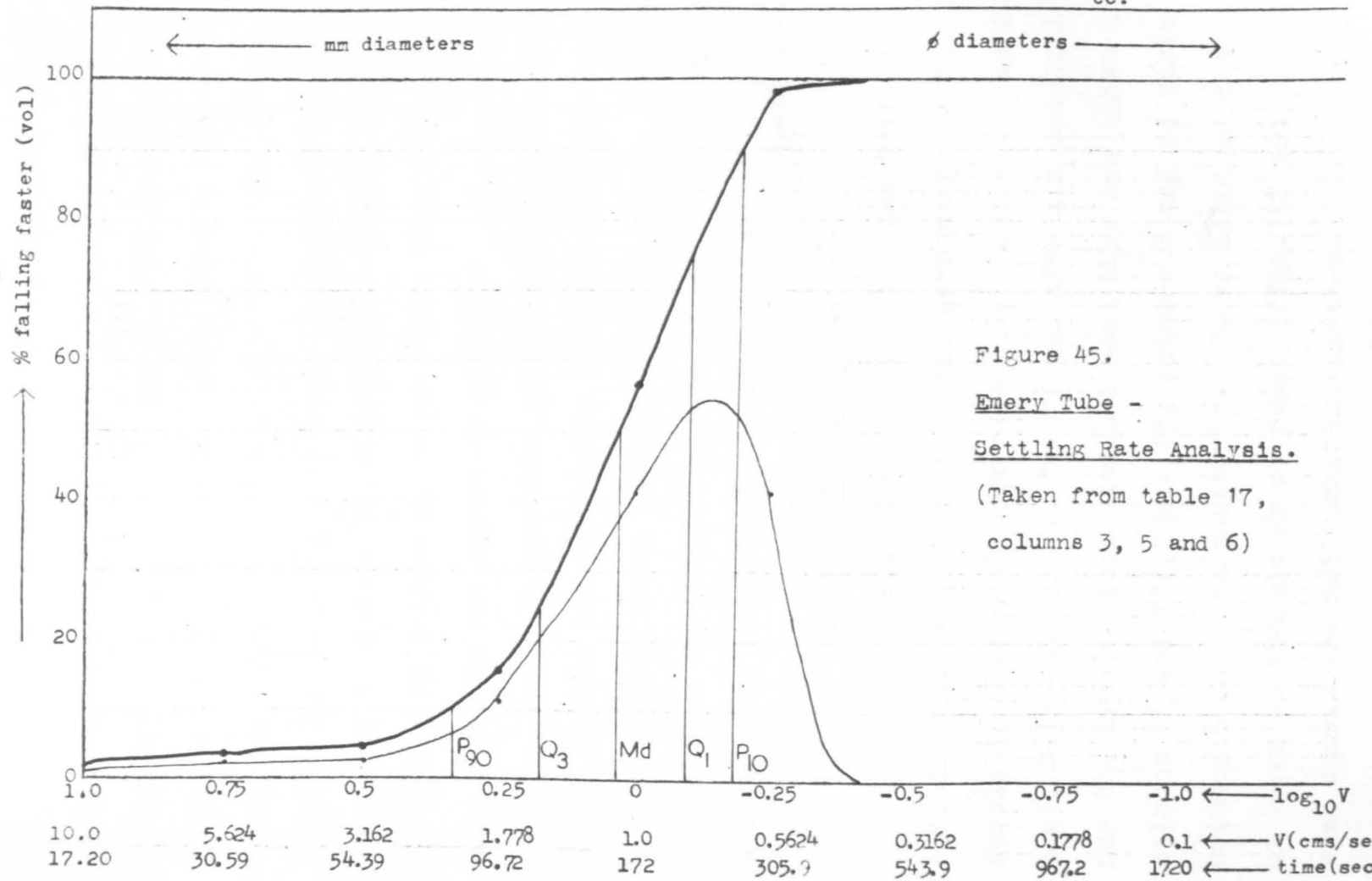


Figure 45.

Emery Tube -

Settling Rate Analysis.

(Taken from table 17, columns 3, 5 and 6)

Sieve Results.

The weights of material in each grade are recorded in table 18, column 4. The sieve intervals are fixed and correspond to values of d in mm and phi (columns 1, 2, and 3). The sum of the grade weights are checked with the total and each is converted to a percentage of the sum of the weights (in this case, 17.809 gms.). These grade percentages are converted to cumulative percentages (column 5) and plotted against ϕ on arithmetic graph paper (fig. 46). The simple size curve is not generally plotted.

N.B. In the rare cases where a large proportion (>10%) of the material being sieved is greater than Sieve Mesh 5 (for example beach sand and boulder clay), the longest diameter of the largest pebble is measured by hand and this phi value is plotted on 0% cumulative.

Combined Sample Data.

This is derived from the two fractions by reducing each set of data by the percentage of the total sample in that grade (expressed as a decimal fraction, in this case, 0.15 and 0.85). The simple size and cumulative data for the hypothetical examples used here are shown in table 12, columns 11 and 12; table 17, columns 8 and 7; table 18, columns 6 and 7 respectively. These combined data are plotted on large arithmetic graph paper (figs. 47 and 48). The simple size curves are not generally plotted.

N.B. It is emphasised that the combined data for the fine fraction always starts at the sand grade percentage.

Table 18. PARTICLE SIZE ANALYSIS - SIEVES

Description of Sample: Fine Sand.

Date: 22nd March 1963

Sand Grade % : 15·0

Shaking Time: 20 minutes

Max. BS Mesh Tolerance (mm)	1 Sieve Mesh No.	2 Mesh Diameters m.m.	3 Mesh Diameters ϕ	4 WT gms	5 WT; % oversize of Total Sand Grade only — SIMPLE SIZE FREQUENCY	6 WT; % oversize of Total Sand Grade only — CUMULATIVE FREQUENCY	7 WT; % oversize of Total Sample — SIMPLE SIZE FREQUENCY	8 WT; % oversize of Total Sample — CUMULATIVE FREQUENCY
3·722	5	3.353	-1.750	0·0	0·0	0·0	0·0	0·0
2·304	8	2.057	-1.025	0·0	0·0	0·0	0·0	0·0
1·574	12	1.405	-0.550	0·0	0·0	0·0	0·0	0·0
0·972	18	0.853	+0.200	0·0	0·0	0·0	0·0	0·0
0·695	25	0.599	+0.700	0·0	0·0	0·0	0·0	0·0
0·498	36	0.422	+1.200	0·182	1·0	1·0	0·1	0·1
0·360	52	0.295	+1.720	0·106	0·6	1·6	0·1	0·2
0·264	72	0.211	+2.200	0·119	0·7	2·3	0·1	0·3
0·230	85	0.178	+2.420	0·136	0·8	3·1	0·1	0·4
0·201	100	0.152	+2.650	0·274	1·5	4·6	0·3	0·7
0·147	150	0.104	+3.250	4·187	23·5	28·1	3·5	4·2
0·116	200	0.076	+3.650	9·047	50·8	78·9	7·6	11·8
0·104	240	0.064	+3.900	3·763	21·1	100·0	3·2	15·0
	Sum of Sand Grades			17·874				
	Total Sand Grade			17·809				

SAND GRADE - GRAPH NOS. 1 a & b. SAMPLE SHEET NO.

WEIGHT PERCENTAGE OVERSIZE VS PHI DIAMETERS - (a) CUMULATIVE FREQUENCY CURVE

(b) SIMPLE SIZE FREQUENCY CURVE

(N.B. ALL PERCENTAGES ARE of SAND GRADE ONLY).

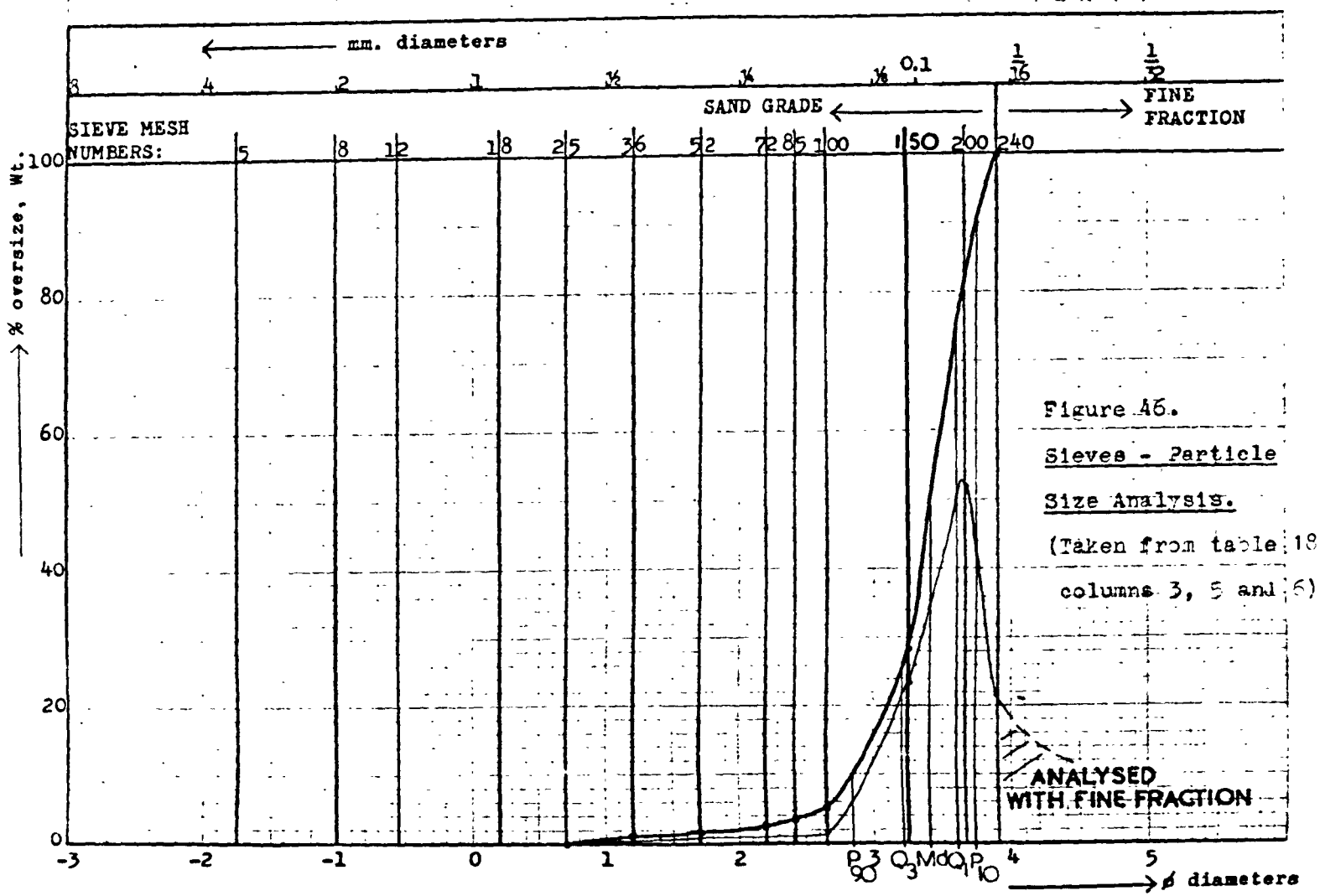


Figure 46.

Sieves - Particle Size Analysis.

(Taken from table 18, columns 3, 5 and 6)

SEDIMENTATION RATE ANALYSIS - ALL GRADES SAMPLE SHEET NO.

GRAPH NOS. 1a & b.

PERCENTAGE FALLING FASTER THAN V, VS $\log_{10}$ SETTLING VELOCITY ($\log_{10}$V)

(a) CUMULATIVE FREQUENCY CURVE

(b) SIMPLE FREQUENCY CURVE

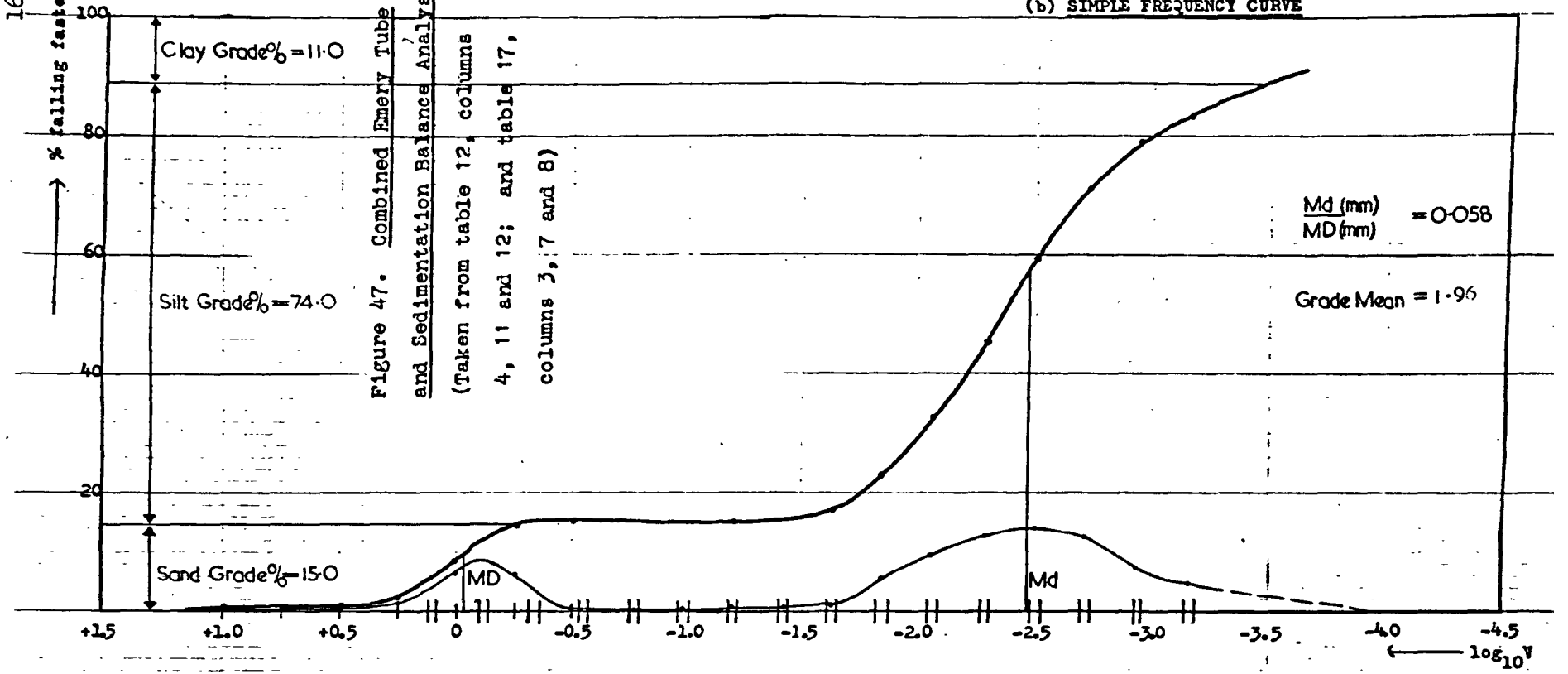


Figure 47. Combined Emery Tube and Sedimentation Balance Analysis.

(Taken from table 12, columns 4, 11 and 12; and table 17, columns 3, 7 and 8)

PARTICLE SIZE ANALYSIS - ALL GRADES : GRAPH NOS. 1a & b.
WEIGHT PERCENTAGE OVERSIZE VS PHI DIAMETERS

(a) CUMULATIVE FREQUENCY CURVE
(b) SIMPLE SIZE FREQUENCY CURVE

SAMPLE SHEET NO.

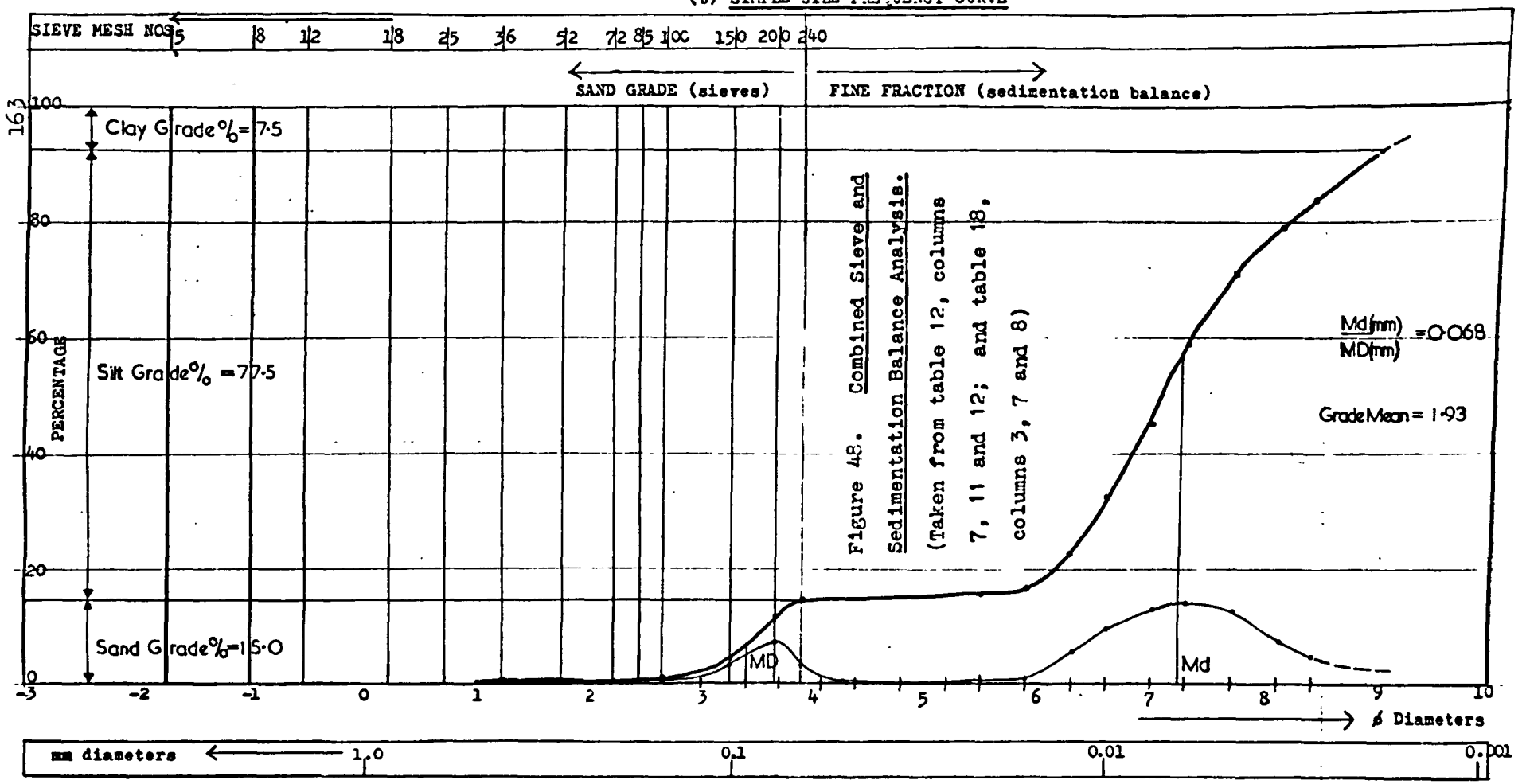


Figure 48. Combined Sieve and Sedimentation Balance Analysis. (Taken from table 12, columns 7, 11 and 12; and table 18, columns 3, 7 and 8)

Chapter 12. Testing the Accuracy and Reproducibility of the Techniques for Mechanical Analyses.

The accuracy of the techniques is difficult to assess directly; in these tests the reproducibility is taken as a measure of accuracy. The four test samples, described in Chapter 7, were used here for the tests.

Quartering by Hand and Sand Grade Percentages.

The criterion for accuracy was chosen as the reproducibility of a series of sand grade determinations. Test sample 1 was used as follows: A portion of the sample was divided up as shown in figure 49 to give, before ignition, three large subsamples and four small subsamples and, after ignition, three large subsamples and four small subsamples. Each portion was wet sieved and the sand grade percentages determined. The results are shown in table 19.

The results appear to be satisfactory. The portions of a sample obtained by quartering are taken as representative of that sample, the sand grade percentages are taken as reproducible, the result after ignition is similar to that before and the former is always used in this work.

Splitting and Sieving Sand Material.

Test sample 4 was used in both splitters as shown in figure 50 to give bulk data and data for seven small portions (each splitter). Each portion was sieved and the cumulative data examined (table 20).

Either splitter appears to give satisfactorily reproducible results in the sieves which are taken as representative

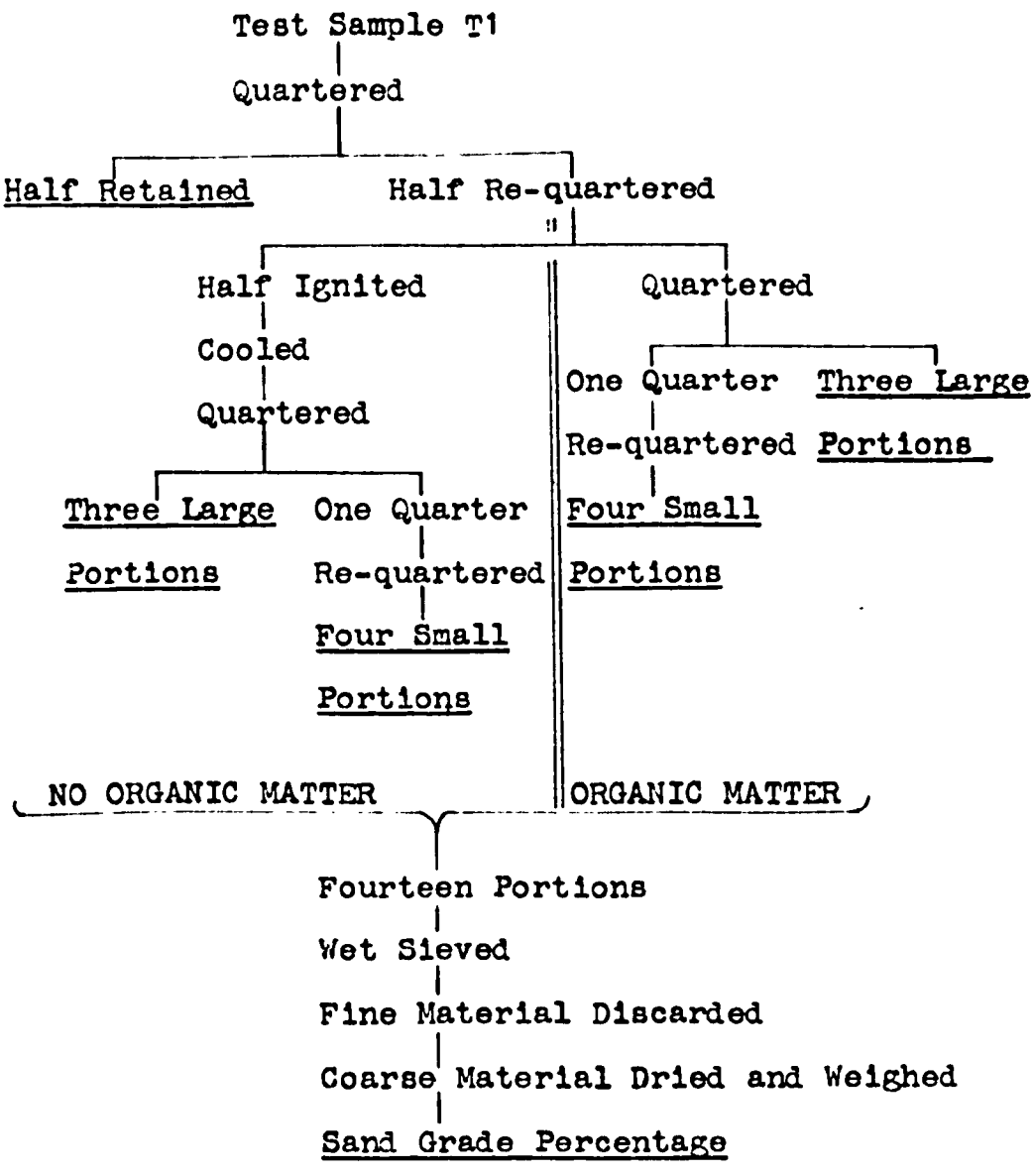


Figure 49. Tests for Quartering by Hand and Wet Sieving.- Flow Sheet.

Table 19. Quartering by Hand - Results of Tests.

a. With Organic Matter.

	Split No. 1	Split No. 2	Split No. 3	Split No. 4	Split No. 5	Split No. 6	Split No. 7
Wt. (gm)	3.505	4.250	3.951	1.253	1.503	0.961	1.120
Sand %	17.5	15.9	16.1	19.5	16.3	17.7	17.8

Average Sand Grade Percentage: 17.3

b. Without Organic Matter.

	Split No. 1	Split No. 2	Split No. 3	Split No. 4	Split No. 5	Split No. 6	Split No. 7
Wt. (gm)	4.487	3.671	3.630	0.820	1.417	1.113	0.987
Sand %	16.9	17.8	17.6	17.1	15.4	16.3	17.2

Average Sand Grade Percentage: 16.9

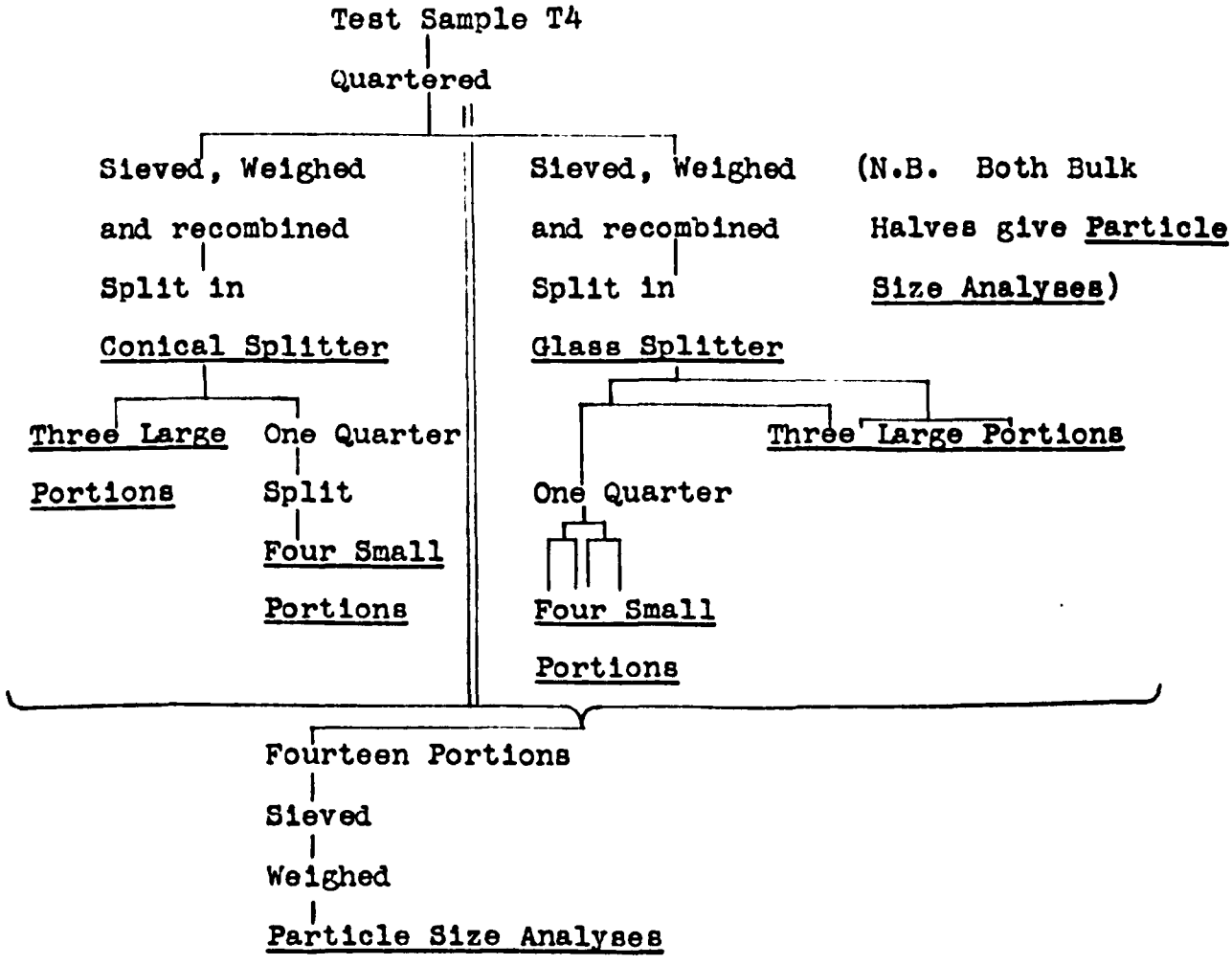


Figure 50. Tests for Sample Splitting and Dry Sieving.

Table 20. Preliminary Splitting and Sieving Tests.

a. Conical Splitter.

(Weight Percentage Oversize)

Sieve	Split 1	Split 2	Split 3	Split 4	Split 5	Split 6	Split 7	Bulk
Mesh No.	6.802gm	6.511gm	7.123gm	1.871gm	1.915gm	1.622gm	2.051gm	29.2
25	0	0	0	0	0	0	0	0
36	38.5	40.0	41.0	42.0	39.5	40.5	41.5	41.0
52	88.5	87.5	87.0	87.5	87.5	87.0	89.0	87.5
72	98.5	98.0	97.5	98.0	97.5	98.0	98.0	98.5
85	99.5	99.0	99.5	98.5	99.0	99.5	99.5	99.5
100	100	100	100	100	100	100	100	100

b. Glass Splitter.

(Weight Percentage Oversize)

Sieve	Split 1	Split 2	Split 3	Split 4	Split 5	Split 6	Split 7	Bulk
Mesh No.	4.221gm	4.571gm	4.251gm	1.152gm	1.091gm	1.053gm	1.095gm	18.2
25	0	0	0	0	0	0	0	0
36	38.5	37.5	35.5	36.0	36.5	36.0	37.5	37.5
52	83.5	84.0	83.5	83.0	82.0	82.5	81.5	83.0
72	98.0	97.5	98.5	98.0	98.0	98.0	98.5	98.0
85	99.0	100	98.5	98.5	98.5	98.5	99.5	99.5
100	100	100	100	100	100	100	100	100

of the coarse material. The conical splitter is used throughout in this work. The sieves appear to give satisfactory results.

Emery Tube.

Test sample 4 was used here. It was first sieved and divided into three fractions: Sieve Mesh Nos. 18 - 25 ("Coarse"), 25 - 52 ("Medium"), 52 - 72 ("Fine"). Four artificial mixtures of these were prepared as follows:

EP1. Equal proportions of the three.

EP2. High proportion of "coarse", low "medium", and "fine".

EP3. High proportion of "medium", low "coarse", and "fine".

EP4. High proportion of "fine", low "coarse," and "medium".

Each of these four were analysed in the Emery Tube three times; the results are shown in table 21. Reproducibility appears to be satisfactory so that one analysis only is considered necessary for the samples in the main study. The particle size results obtained from the Emery Tube and a comparison with sieve results from the same meterial is considered in another section (Chapter 15).

Sedimentation Balance.

Two specimens of diatomaceous earth were analysed in the Sedimentation Balance and the particle size results found to be almost identical with those specified by the manufacturers. Also test samples 1 and 2 were used to make sufficient suspension volume for two identical analyses and the results for each pair compared.

Dispersion for Particle Size Suspensions. Weigner's (cited in von Andreason, 1956) criterion for a stable or

Table 21. Preliminary Emery Tube Tests - Results.

Percentages of Total Sample settling faster than v.

Log 10	v	EP1				EP2				EP3				EP4			
		1	2	3	Av	1	2	3	Av	1	2	3	Av	1	2	3	Av
1.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.75		50.3	50.3	48.9	49.8	54.2	54.2	55.5	54.6	32.8	34.2	32.1	33.0	22.1	22.1	20.8	21.7
0.50		99.6	99.1	97.8	98.8	96.1	95.5	96.8	96.1	96.9	95.0	98.1	96.7	84.5	84.5	85.8	84.9
0.25		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

perfectly dispersed suspension of solid particles in a liquid medium is that the particle size results should be independant of the concentration of solid in suspension, provided that the concentration is less than the critical 25 gms/L. Thus solid concentrations were varied in the different dispersing solut--ions and the results compared.

Dispersing Solutions: (Cohen, 1959; von Andreason, 1956; Hillier, 1955; and Krumbein and Pettijohn, 1938) Calgon or sodium hexametaphosphate is used as the dispersing solution throughout because of its wide applications in the range of fine grained material from clays to soils. Powdered crystalline calgon is dissolved in distilled water in three different concentrations for these initial tests: 8, 4, and 2 percent by weight. They were brought to a pH of 8.3 with phenolphthalein and sodium carbonate.

Suspensions: These were prepared as shown in table 22a. They were boiled at reduced pressure, made up to the mark with distilled water, and stirred. The results are shown in table 22b, It is seen that similar results were obtained from most suspensions of test sample 1 (SP3 - SP8; SP11) and test sample 2 (SP 9, 10 and 12).

The reproducibility is considered satisfactory and thus it is inferred that accuracy is as well. Applying Weigner's criterion for a stable suspension, the three dispersing solutions are satisfactory (N.B. tap water is not) for both organic and non organic material. The 2% solution is always used in this study.

N.B. It is realised that the viscosity values of the 4 and 8 % solutions were not accurate but the tests remain valid.

Table 22. Preliminary Sedimentation Balance Tests.

a. The Suspensions.

Number	Test Sample No.	Conc. of Suspension gm/L	Conc. of Calgon Percent
SP1	I	2	N.B. Tap Water
SP2	II	2	N.B. Tap Water
SP3a,b	II	0.5	8
SP4a,b	II	4	8
SP5a,b	II	0.5	4
SP6a,b	II	4	4
SP7a,b	II	0.5	2
SP8a,b	II	4	2
SP9a,b	I	0.5	2
SP10a,b	I	4	2
SP11a,b	II	2	2
SP12a,b	I	2	2

N.B. SP1 and SP2 were observed to coagulate after about half an hour and the suspensions were clear in an hour and a half.

Table 22. b. Results of the Tests.

Test Sample II (Clayey Material)

Phi	SP3		SP4		SP5		SP6		SP7		SP8		SP11		
Values	a	b	a	b	a	b	a	b	a	b	a	b	a	b	Average
4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.0	4.0	4.5	3.5	3.5	4.5	4.0	5.0	4.5	4.5	3.5	3.5	3.5	4.0	4.5	3.7
6.0	18.0	18.0	18.5	18.0	18.0	17.0	18.0	17.5	17.5	17.0	17.0	17.5	18.0	18.5	17.7
6.5	28.5	29.5	28.5	29.0	28.0	27.5	29.5	29.5	29.5	29.0	29.0	29.0	28.0	29.5	28.8
7.0	44.5	44.0	44.0	42.5	43.5	43.0	43.0	41.5	44.5	45.0	43.5	42.5	44.0	43.5	43.5
7.5	65.0	65.5	66.0	64.0	64.0	65.5	64.0	66.0	64.0	65.5	64.5	64.0	65.0	65.5	65.0
8.0	85.5	86.5	85.5	84.5	85.0	84.0	84.5	84.5	86.5	87.5	86.0	87.5	87.0	84.5	85.6
8.5	94.0	93.0	95.0	94.5	94.0	94.5	95.5	93.5	96.5	95.0	94.5	96.5	96.0	95.5	94.9
9.0	99.5	98.5	99.0	100	98.5	99.5	100	100	100	99.5	98.5	98.0	99.0	99.5	99.3

Test Sample I (Organic Facies)

Phi	SP9		SP10		SP12		
Values	a	b	a	b	a	b	Average
4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.0	3.5	3.0	4.0	3.5	1.5	2.0	2.9
6.0	8.0	7.0	8.5	7.5	6.5	7.5	7.5
6.5	11.5	11.5	12.0	11.0	10.5	11.5	11.3
7.0	16.5	16.0	17.0	17.5	16.0	15.5	16.4
7.5	23.5	23.0	24.0	23.5	23.5	24.0	23.6
8.0	31.5	30.0	31.5	30.5	31.5	32.0	31.2
8.5	40.0	41.5	40.0	40.5	41.0	40.0	40.5
9.0	52.0	51.0	51.5	54.0	53.5	52.5	52.4

Chapter 13. Treatment of Frequency Curves.

Definitions of Terms Used in this Section, also in Chapters 11 and 12.

Frequency Distribution. A set of measurements of proportion; the same frequency distribution data may be represented graphically in two ways.

Frequency (Density) Curve. The amount of material at any size or, as here, in a certain range of size (sieve, Emery Tube, or Sedimentation Balance grades). Hence these curves are often referred to here as "simple size curves". The size scale against which these proportions are plotted is generally, as here, logarithmic. The proportion at any size ordinate is represented by the area under the curve between that size ordinate and the next one up the scale. Thus the total area is crucial as it represents one hundred percent of the observations; also the percentiles are measured in terms of area, so that the 50 percentile or median is that size ordinate which divides the area into two equal halves; and that which has $\frac{3}{4}$ area to the right and $\frac{1}{4}$ area to the left is the 25 percentile.

Cumulative (Frequency) Curve. The total amount of material above a certain size is plotted against the logarithmic size scale. The proportion larger than any size ordinate is represented by the height of the curve at that ordinate. Thus the total height is crucial as it represents one hundred percent of the observations; the 50 percentile or median is that size ordinate which intersects the curve at exactly half its total height. This form of the frequency distribution is used in this work for calculating the data, though illustrations are often made using the frequency curve.

Features of these Curves.

Mode or Maximum. This value is the size ordinate of the maximum height of the frequency curve; it is generally approximately equal to the median (see below).

Antimode or Minimum. This value is the size ordinate of the minimum height of the density curve; it only occurs when there are two or more maxima.

Group. This term includes all the material present in a unimodal distribution (see below), but it is a useful concept in the bimodal distributions considered later. In these latter the observations are grouped together in two concentrations around the two modes; each concentration is termed a group. The groups manifest themselves as two peaked areas with a trough between them on the bimodal frequency curves. On the cumulative curves there is a corresponding flat portion separating the two steeper portions representing the two groups (figs. 47 and 48).

Types of Curve.

Unimodal. A curve with one mode, one group, one maximum on the frequency curve, and one point of inflexion on the cumulative curve.

Bimodal. A curve with two modes, two groups, two maxima on the frequency curve and therefore one minimum between them, and three points of inflexion on the cumulative curve of which the central one corresponds to the minimum.

Polymodal. A curve with an unstated number (more than two) of modes.

Normal Curve. This form of the frequency curve commonly occurs in natural distributions (e.g. biology). It is a family of curves which have been strictly defined mathematically (like the

straight line, the circle, and the ellipse). It is not discussed at length here but it can be referred to on p. 230 of Mosteller, Rourke, and Thomas (1961). Natural particle size distributions often nearly follow a log normal curve in which the particle size scale is logarithmic. The standard deviation of a normal curve is a comparison of those percentiles which include between them and the curve the central two thirds of the total area, and exclude one sixth each side.

Independant Fractions.

The arbitrary division between the coarse fraction (particles larger than 0.064 mm) and the fine fraction (particles smaller than 0.064 mm) has already been defined. It is emphasised that it is independant of features of the frequency distributions.

The geological interpretations of the curves with respect to the true mechanical distributions are considered in Part III. A mechanical distribution refers to the physical "genetic" processes of deposition (settling rate, particle size).

Bimodality of Windermere Material.

The general scheme of analyses (fig. 38) leads to combined a, b, c, and d analyses of organic samples and to combined c and d analyses only of non organic samples (table 23). Many combined curves drawn here had bimodal frequency distributions with the minimum near $\phi 4.0$ (0.064 mm), the division between the fractions (figs. 47 and 48). The most convenient mathematical method for treating these bimodal distributions for sedimentological purposes was to separate each of them into the coarse and fine groups which are, in fact, approximately equivalent to the respective fractions (figs. 47 and 48). Therefore separate treatment of sieve and/or

Table 23. Mechanical Analyses of Organic Samples.

1.	Sand Grade Percentage Before Ignition.	
2.	Sand Grade Percentage After Ignition.	
3.	Particle Size (Sieve) Data of Coarse Material.	Data combined in proportion of 1. (above) to give: a./ COMBINED PARTICLE SIZE ANALYSES BEFORE IGNITION.
4.	Particle Size ("Stokes'") Data of Fine Material (dispersed).	
5.	Settling Rate (Emery Tube) Data of Coarse Material.	Data combined in proportion of 1. (above) to give: b./ COMBINED SETTLING RATE ANALYSES BEFORE IGNITION.
6.	Settling Rate (Sedimentation Balance) Data of Fine Material (undispersed).	
7.	Particle Size (Sieve) Data of Coarse Material.	Data combined in proportion of 2. (above) to give: c./ COMBINED PARTICLE SIZE ANALYSES AFTER IGNITION.
8.	Particle Size ("Stokes'") Data of Fine Material (dispersed).	
9.	Settling Rate (Emery Tube) Data of Coarse Material.	Data combined in proportion of 2. (above) to give: d./ COMBINED SETTLING RATE ANALYSES AFTER IGNITION.
10.	Settling Rate (Sedimentation Balance) Data of Fine Material (undispersed).	

Emery Tube data for the coarse fraction, which is approximately equal to the coarse group, and of Sedimentation Balance data for the fine fraction, which is approximately equal to the fine group, is performed individually for each sample. This is based on the assumption that the two groups revealed by the curve exactly coincide with the two fractions. It has been explained that this is not strictly true, but it is considered of greater importance that the mechanical data are obtained by an exactly reproducible method. In this respect, accurate distinction of the groups proved doubtful. There is no statistical necessity for this separation into groups (or fractions); the sedimentological results, however, are more specific and more significant than "bimodal results".

N.B. Samples with less than 5% of coarse fraction did not provide for satisfactory sieve or Emery Tube analyses. The fine fraction only was examined in these cases.

Graphical Calculation of Mechanical Data.

"Size" Ordinates.

The logarithmic "size" ordinates are read off the cumulative curves (figs. 43, 44, 45, and 46), they are listed in table 24a. Phi values (logarithmic) are converted into mm (arithmetic). $\text{Log}_{10} v$ values are converted into cms/sec, and then into mm using Rubey's General Formula (fig. 21).

Statistical Data. (table 24b)

These are calculated from mm ordinates (Pettijohn, 1957, Chapter 2). The median represents the curve's position on the scale; sorting, skewness, and kurtosis represent its shape (including slope). These properties may be used as a guide to the sedimentological history of the material which gave the curve.

Table 24. Statistical Analyses of Cumulative Curves.

a. "Size" - Ordinates.

Ordinate.	Percentile.	Abbreviation.
"Ninety - Percentile"	10	P90
Third Quartile	25	Q3
Median	50	Md
First Quartile	75	Q1
"Ten - Percentile"	90	P10

b. Statistical Data. (also see Pettijohn, 1957, table 9)

Statistical Measure.	Calculation.	Abbreviation. (Fine/Coarse).
Median Diameter	Md.	MD/Md
Coefficient of Sorting	$(Q3/Q1)^{\frac{1}{2}}$.	SO/So
Coefficient of Skewness	$(Q3 \cdot Q1)/Md^2$.	SK/Sk
Sign of Skewness	Sign of $\log_{10}$ Sk.	
Coefficient of Kurtosis	$\frac{(Q3 - Q1)}{2(P90 - P10)}$.	K/k

N.B. These statistical data are discussed in the text and illustrated (fig. 51).

Table 24. c. Calcalation of Data from figures 43, 44, 45, 46.

Ordinates		fig. 43; (v)	fig. 44; (ø)	fig. 45: (v)	fig. 46; (ø)
	ø; log v	-1.88(ø:6.38)	6.30	0.34(ø:2.67)	2.84
P90	v(cm/sec)	:0.0125		:2.05	
	d(mm)	:0.0120*	:0.0127*	:0.160	:0.140
	ø; log v	-2.14(ø:6.79)	6.70	0.175(ø:3.00)	3.20
Q3	v(cm/sec)	:0.0070		:1.45	
	d(mm)	:0.0090*	:0.0096*	:0.125	:0.110
	ø; log v	-2.47(ø:7.38)	7.25	0.030(ø:3.25)	3.40
Md	v(cm/sec)	:0.0032		:1.05	
	d(mm)	:0.0060*	:0.0065*	:0.104	:0.095
	ø; $\log_{10}$v	-2.93(ø:8.17)	8.16	-0.090(ø:3.46)	3.60
Q1	v(cm/sec)	:0.0011		:0.780	
	d(mm)	:0.0035*	:0.0035*	:0.091	:0.083
	ø; log v	-3.69(ø9.39)	9.13	-0.180(ø:3.63)	3.73
P10	v(cm/sec)	:0.0002		:0.620	
	d(mm)	:0.0015*	:0.0018*	:0.081	:0.075
Primary Data					
Median "Diameter"		0.0060 mm*	0.0065 mm*	0.104 mm	0.095 mm
Sorting		1.62*	1.65*	1.17	1.15
Skewness		0.86*	0.83*	1.05	1.01
Kurtosis		0.25*	0.26*	0.24	0.22

* These pairs of values should, ideally, be identical because they are both derived from the same Sedimentation Balance results. The errors are caused by curve - drawing and Conversion Charts; they represent the extent of the error to be expected in this part of the work. this does not apply to the results from the coarse material because they are derived in the Emery Tube and the Sieves respectively.

Extrapolation of Curves. It has been mentioned that results from Windermere are often incomplete because the material is too fine (Chapter 9). Thus many cumulative curves are extrapolated in order to obtain the required ordinates and statistical data. The following ruling was made in this respect: curves where the last coordinate is at less than 50% (vertical axis) are always extrapolated up to this percentage to give the median; otherwise the curves are not extrapolated by more than 10%. Thus 65% and 80% are the lowest values that give Q1 and P90 respectively. There are three possibilities in this respect:

a. P90, Q3, and Md giving Md only.

b. P90, Q3, Md, and Q1 giving Md, So, and Sk.

c. P90, Q3, Md, Q1, and P10 giving Md, So, Sk, and k.

N.B. Examples of the calculations are shown in table 24c.

Mathematical Significance of the Statistical Data.

The data represent the mechanical distributions, thus the significances of the values are explained below; this is necessary before they are used for sedimentological interpret-ations. It is also useful to illustrate these four properties applying to both a cumulative and a frequency curve (fig. 51). Skewness and kurtosis have standard values for normal distributions and Friedman (1962 , p. 741) claims that departures from the log normal curve are indicative of various sedimentary environments.

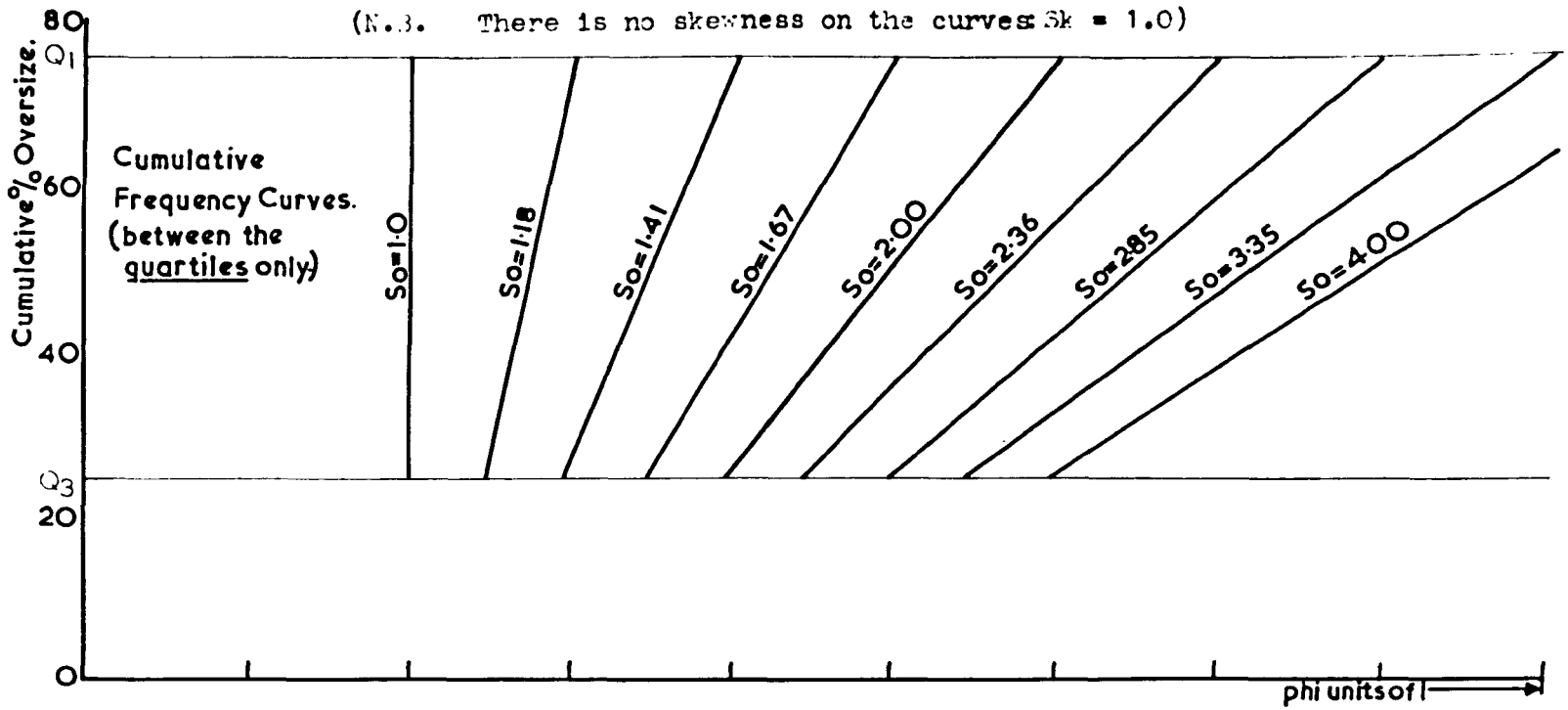
Median Diameter. Taken as representative of coarseness or fineness of material giving the curve; exactly equal to the mode or maximum only when there is no skewness on the curve.

Coefficient of Sorting (fig. 51a). This value is taken as repres-entative of the "dispersion" of material (Spencer, 1963). Friedman (1962) says that it represents standard deviation only in well

Figure 51. Representation of Statistical Data by Theoretical Curves.

a. Sorting.

(N.B. There is no skewness on the curves: Sk = 1.0)



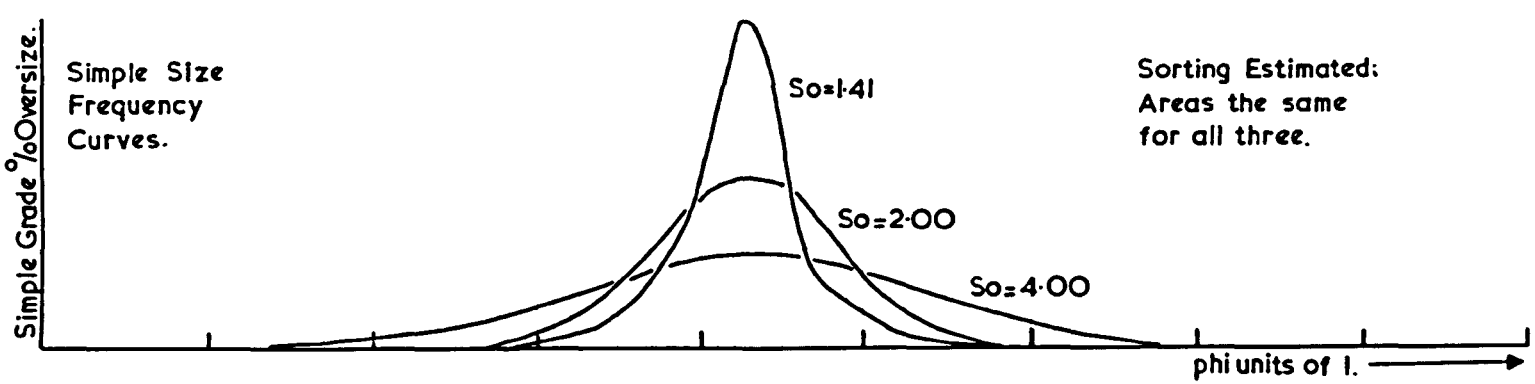


Figure 51. b. Skewness.

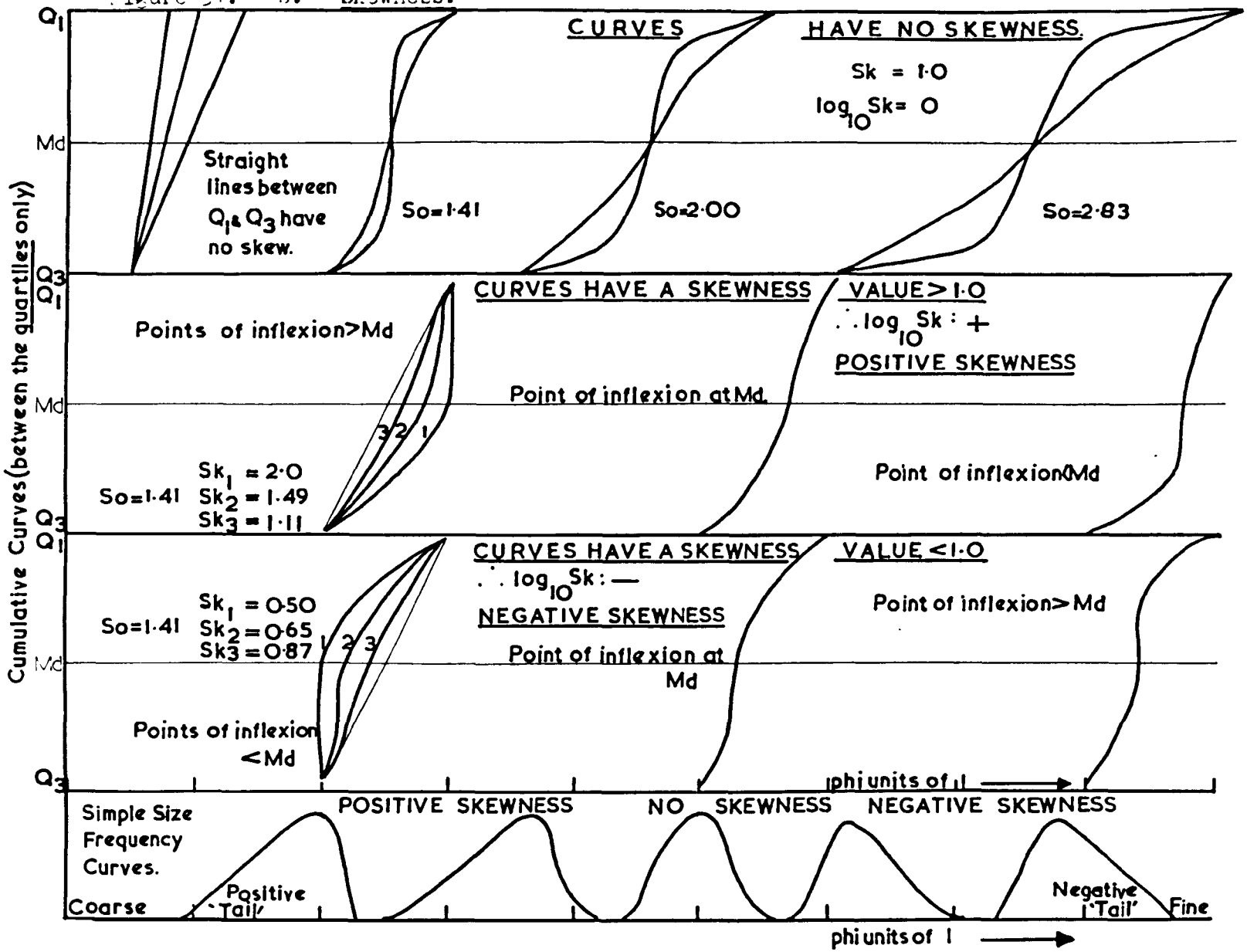
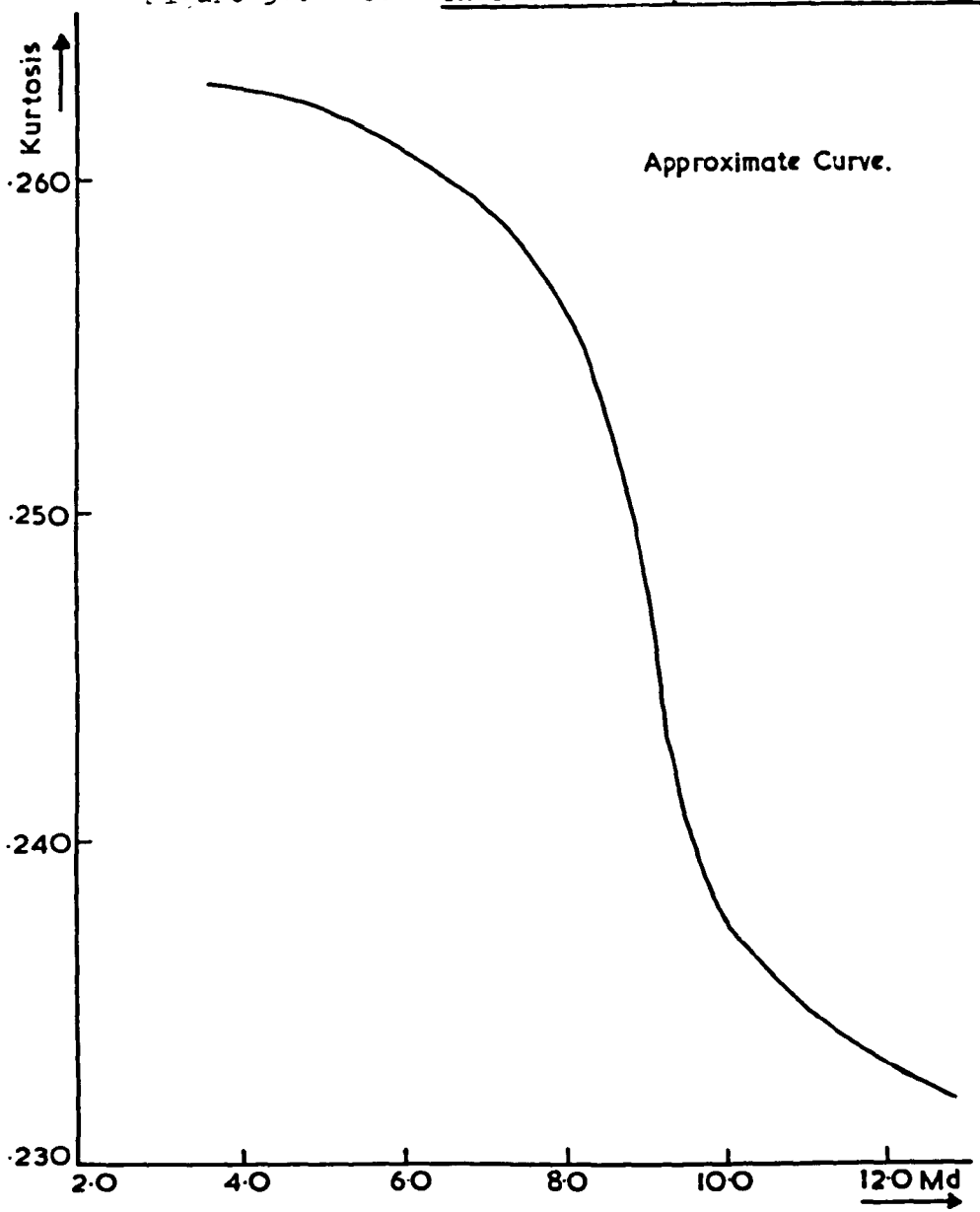
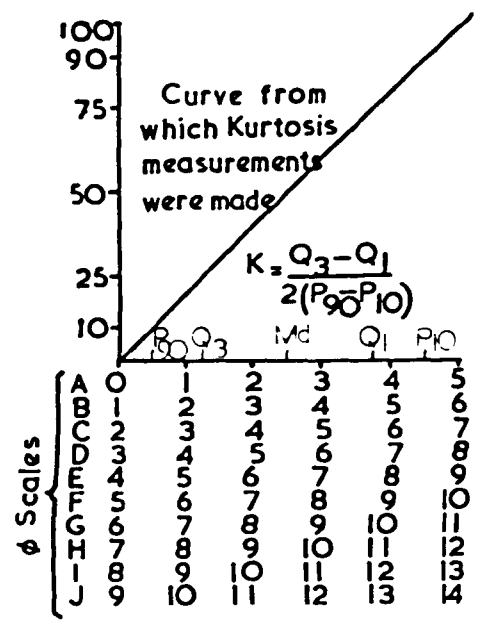


Figure 51. c. Theoretical Experiment: Md vs k_{mm}, $k\phi$.

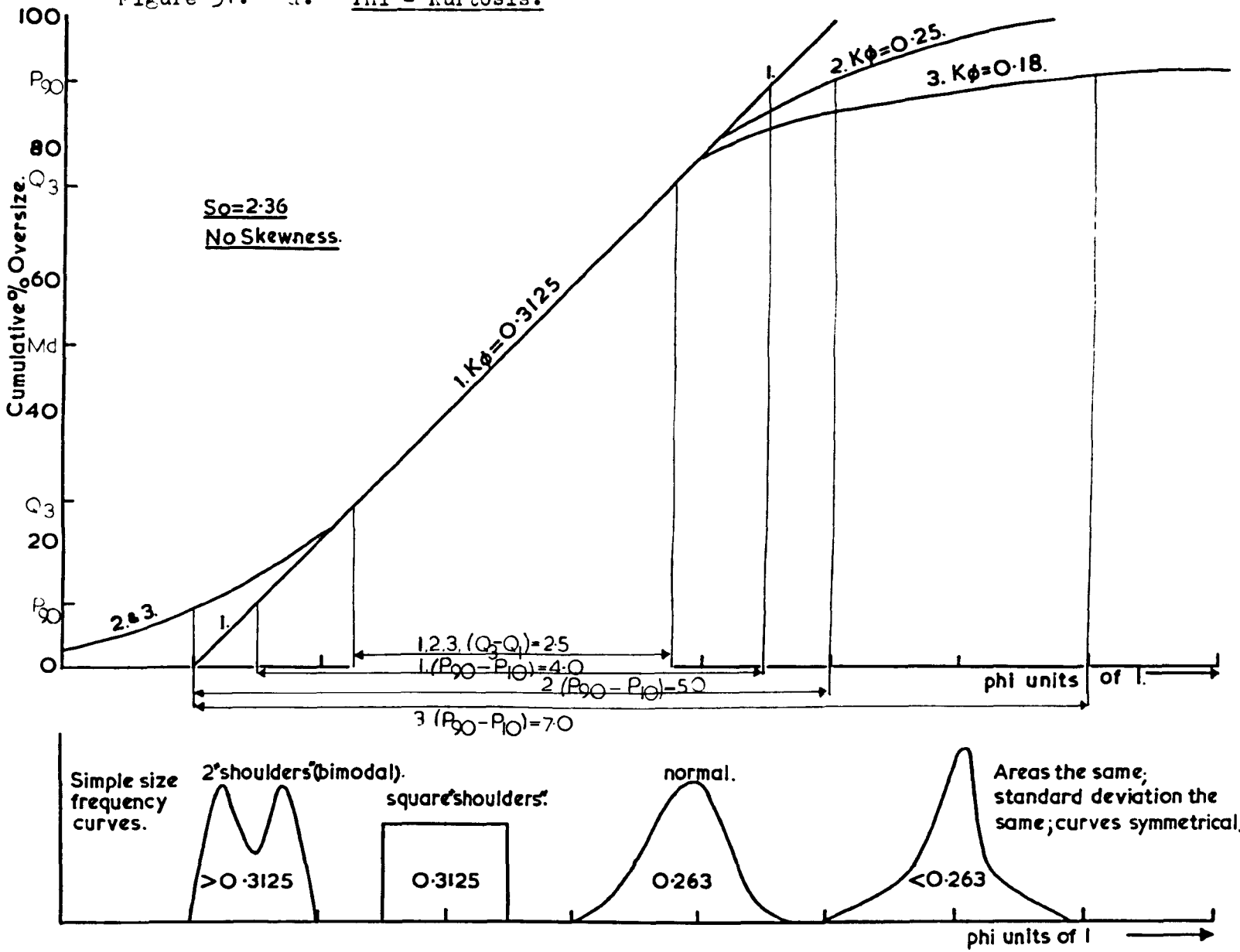




Results

	Md.φ	Kurtosismm	K φ
A	2·5	·2630	·3125
B	3·5	·2628	·3125
C	4·5	·2559	·3125
D	5·5	·2617	·3125
E	6·5	·2598	·3125
F	7·5	·2585	·3125
G	8·5	·2641	·3125
H	9·5	·2406	·3125
I	10·5	·2358	·3125
J	11·5	·2340	·3125

Figure 51. d. Phi - Kurtosis.



sorted sediments. N.B. The same slope on the cumulative curve between the quartiles is denoted by the same sorting value at all sizes because it is a simple arithmetic ratio taken off a logarithmic scale.

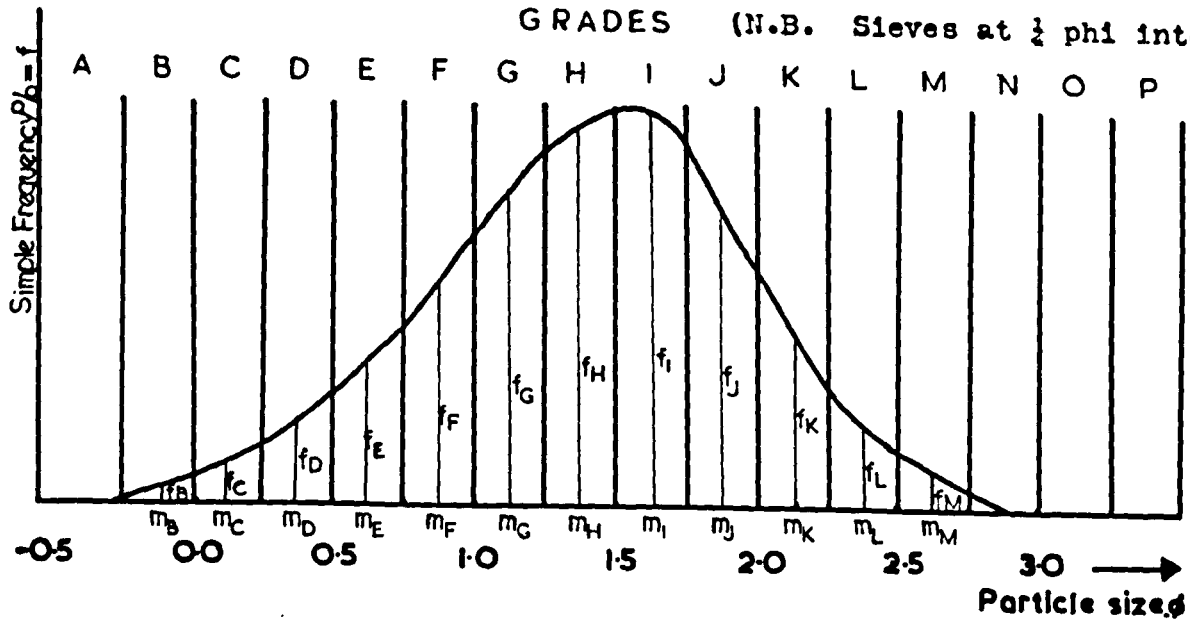
Coefficient of Skewness (fig. 51b). This value is taken as representative of the lack of symmetry of the distribution curve (table 24b); this is because the further the Sk value departs from 1.0, the less symmetrical the curve is. Folk (personal communication, 1962) suggests that this is an insufficiently sensitive measure because it only accounts for the central 50% of the curve. If the entire distribution curve had always been available, it would have been adviseable to use the moments shown in figure 52. N.B. The same degree of symmetry on the curve is denoted by the same skewness value at all sizes because it is an arithmetic ratio of products taken off a logarithmic scale. Sk for the log normal distribution is 1.00.

Coefficient of Kurtosis. This is an arithmetic ratio of differences (mm) taken off a logarithmic scale. Therefore the same shape of curve is not denoted by the same kurtosis value at all sizes; this is shown in figure 51c where a graph of kurtosis against median , for a series of theoretical straight line distributions, indicates the extent of this variation. Therefore it was decided to calculate kurtosis directly from the phi values of the ordinates before conversion to mm. This is in contrast to the calculations of the other data but it is valid. The kurtosis value (phi) for all straight line distributions is 0.3125 (fig.51c), this is taken as the maximum for unimodal frequencies(a higher kurtosis value would indicate a bimodal curve, see below).

The significance of kurtosis is shown in figure 51d. It is a subtle property of a curve relating the "shoulders" to the "tails"and the peak; the quartiles can be spread out with respect to the ten and ninety percentiles, thereby increasing the value of kurtosis, only by building up the shoulders of the curve. Thus 0.3125 represents square shoulders and higher values indicate bimodality. Values increasingly smaller than 0.3125 show the peak and tail increasing in importance at the expense of the shoulders. Kurtosis is therefore a measure of the prominence of shoulders. It is emphasised that k, as measured here following Pettijohn (1957), is on a different scale from that used in other branches of statistical application; the more usual "fourth moment" (shown in fig. 52) takes a low value for a curve with prominent shoulders. k for the normal distribution is 0.263 (measured from table III; Mosteller, Rourke, and Thomas, 1961, p.432). It would have been adviseable again to use the moments method (fig. 52) if the entire distribution curve had been available in each case. Kurtosis is a very uncertain property of mechanical distributions of geological material. Its significance has rarely been discussed at length and this work adds little to previous knowledge.

Further Considerations.

There are other similar data obtained from more closely spaced percentiles on the curve which would furnish further information about mechanical distributions; these are not used here. Figure 52 shows an example of the moments method, as opposed to the graphical method used here, of calculating data from mechanical distributions. It has already been mentioned, with respect to specific properties, that this method would have been used if the entire distribution had always been available.



Moments are derived from phi - data which are not re - converted to millimetre data. All the moments are derived from the simple frequency curve and are based on the geometry of the log normal curve (Friedman, 1962).

First Moment (Mean); $\bar{x}.$ $= \frac{\sum_{mA}^{mM} fm}{100}$

Standard Deviation (Sorting); 6 $= \frac{\left[\sum_{mA}^{mM} f(m - \bar{x})^2\right]^{\frac{1}{2}}}{100}$

Third Moment (Skewness); $\alpha_3.$ $= \frac{6^{-3}\sum_{mA}^{mM} f(m - \bar{x})^3}{100}$

Fourth Moment (Kurtosis); $\alpha_4.$ $= \frac{6^{-4}\sum_{mA}^{mM} f(m - \bar{x})^4}{100}$

Here the sieve grades are evenly spaced, unlike in the present work. On this basis Sedimentation Balance curves could be used to give these moments, but they generally require extrapolation.

Figure 52. Moments Data for Sieve Analyses. (Folk and Ward. 1957)

Other Mechanical Data. (figs. 47 and 48)

a. Ratio of Median Diameters.

Md/MD.

b. Grades.

Sand Grade Percent (>0.064 mm) x 1 = S.

Silt Grade Percent (0.064 - 0.002 mm) x 2 = 2s.

Clay Grade Percent (<0.002 mm) x 3 = 3c.

N.B. Sand Grade has already been calculated (Chapter 10).

Clay Grade is taken as that percentage undersize at ø9.0 (or $\log_{10} v = 3.45$).

Silt Grade is calculated knowing sand and clay grades.

c. Grade Mean.

Mean = (S + 2s + 3c)/100.

Chapter 14. Flocculation of Fine Material.

(See hypothetical case in figure 53.)

Definition of Flocculation.

The fine material of the same sample was observed to settle more quickly in lake water than in dispersing solution, liquid densities and viscosities being taken into account. This was taken to be due to flocculation of the sample in lake water. It is not strictly a mechanical property but a quantitative study of it is best made from calculations based on the mechanical analyses.

Calculation of the Degree of Flocculation.

The cumulative frequency curves of the fine fractions' particle size (dispersed) and settling rate (undispersed) distributions are compared numerically as shown in figure 53. The flocculating suspension generally settles more slowly than the dispersed suspension initially but settles considerably faster ultimately. The values:

a. Maximum Percentage of Flocculation (c and b analyses),

b. The Particle Size at which this occurs,

are taken from the flocculation curve.

In practice a flocculation curve is not drawn for each sample calculation; the values are assessed to the nearest half-phi ordinate. The curve shown in figure 53 is typical of those from lake sediments and it was hoped that a mathematical expression could be derived to denote the form of each curve as a single value. This would have contained functions and const--ants applicable to a set of variables taken off each curve. However such an expression could not be derived because the general form of the curve could not be sufficiently "fixed"

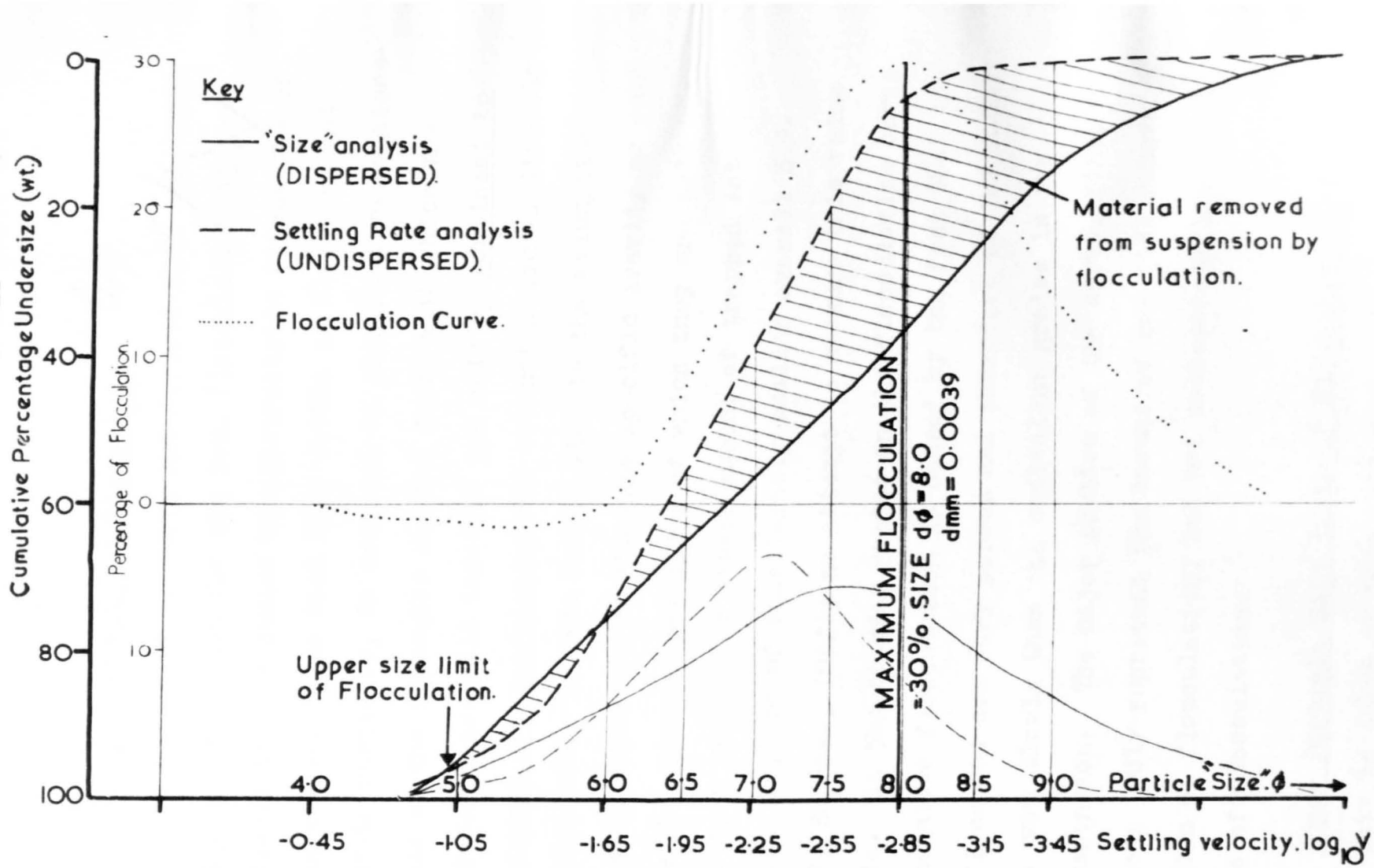


Figure 53. Hypothetical Curves to Illustrate Measurement of Flocculation.

mathematically. Instead the two values mentioned above are used to denote flocculation.

Specific Gravity of Floccules.

The flocculation curve and derived data only give a representative expression for the true flocculation of that sample. Flocculation is caused by electrostatic attraction of particles in suspension so that they settle as floccules and not as discrete particles, in contrast to dispersed suspensions. The true size of the floccules and the force with which the discrete particles are held together are only proportional to the actual degree of flocculation and are not measured directly here. The main error in this method lies in the assumption that all the floccules are of the same specific gravity as each other and as the discrete particles of which they are made up. In fact, due to a greater or lesser amount of trapped inter-stitial water, they are of considerably smaller overall S.G. (Rolfe, 1957; Sherman, 1953); no attempt to measure this value has been made. In the coarser grades on the flocculation curve the slight negative flocculation is caused by the fact that the the larger floccules are very porous and therefore of low S.G.; these settle more slowly than the equivalent grades in the dispersed suspension. The major portion of the curve, finer than this, does truly represent the amount of material removed from suspension by flocculation, but not necessarily the actual degree of flocculation.

Upper Particle Size Limit of Flocculation.

This is taken as near that grade at which the two curves start to diverge, generally giving negative flocculation.

This was always found to lie between ϕ5.0 and ϕ5.7 (0.030 and 0.020 mm respectively). This result is in the same order as that of Sherman (1953) who found that 0.024 mm is the upper limit of flocculation in Lake Mead, U.S.A.

Maximum Flocculation in Material 0.002 mm.

A number of flocculation curves in this study indicated a maximum flocculation occuring at a particle size smaller than ϕ9.0; the peak did not occur within the measured grades. Extrapolation was impossible so the maximum value was given as (% at ϕ9.0) and the size was given as <0.002 mm. This leads to correlation difficulties (Part III). but it is an inherent limiting factor set by the Sedimentation Balance.

Negative Flocculation.

In certain cases, particularly gyttja samples, the flocculated suspensions settled slower than the dispersed suspensions of the same sample. This is thought to be due to the fact that flocculation in this material was not strong and so the flocculos were very loose and porous in all "size" ranges. The extent of this effect is not measured but it is always denoted as "negative flocculation".

N.B. The flocculation values of the organic lake sediments, ooze and gyttja, were measured; those of the Late Glacial were not because the water settling conditions were not even approximately reproducible.

Chapter 15. The Validity of Certain Analysing Techniques.

Tests to Discover the Nature of Bimodal Curves.

The bimodality of combined curves (figs. 47 and 48) has been described in Chapter 13. It is important to know the significance of this effect, there were two possib-ilities: (N.B. The hypothetical example in figure 54 is not the same as that used to illustrate the calculations, it contains 37% larger than 0.064 mm)

a. It may be due to material which was somehow unaccounted in the fine fraction mechanical analysis (fig. 54a). This is suggested by the fact that the central point of inflexion between the groups is near the arbitrary division between the fractions.

b. The curves may be true representations of the mechanical distributions of the materials concerned (fig. 54, b and c). This possibility is suggested by the slight "tailing off" of coarse fraction curves in the finest sand grades, making the central point of inflexion on the combined curves consistently slightly finer than $\phi 4.0$. This indicates that there are two groups in most lake material. In some cases these appear to overlap (fig. 54c) and in others they do not (fig. 54b). This separation or overlapping in the coarser silt grades would make the treatment of group data, instead of fractional data, speculative with the risk of introducing inconsistencies. This antimodal portion is not therefore studied specifically. These reasons are illustrated in figure 54.

Spencer (1963) postulates that sedimentary material may be "bimodal" (contain a mixture of two "fundamental populat-ion ") and still appear to be unimodal on the frequency

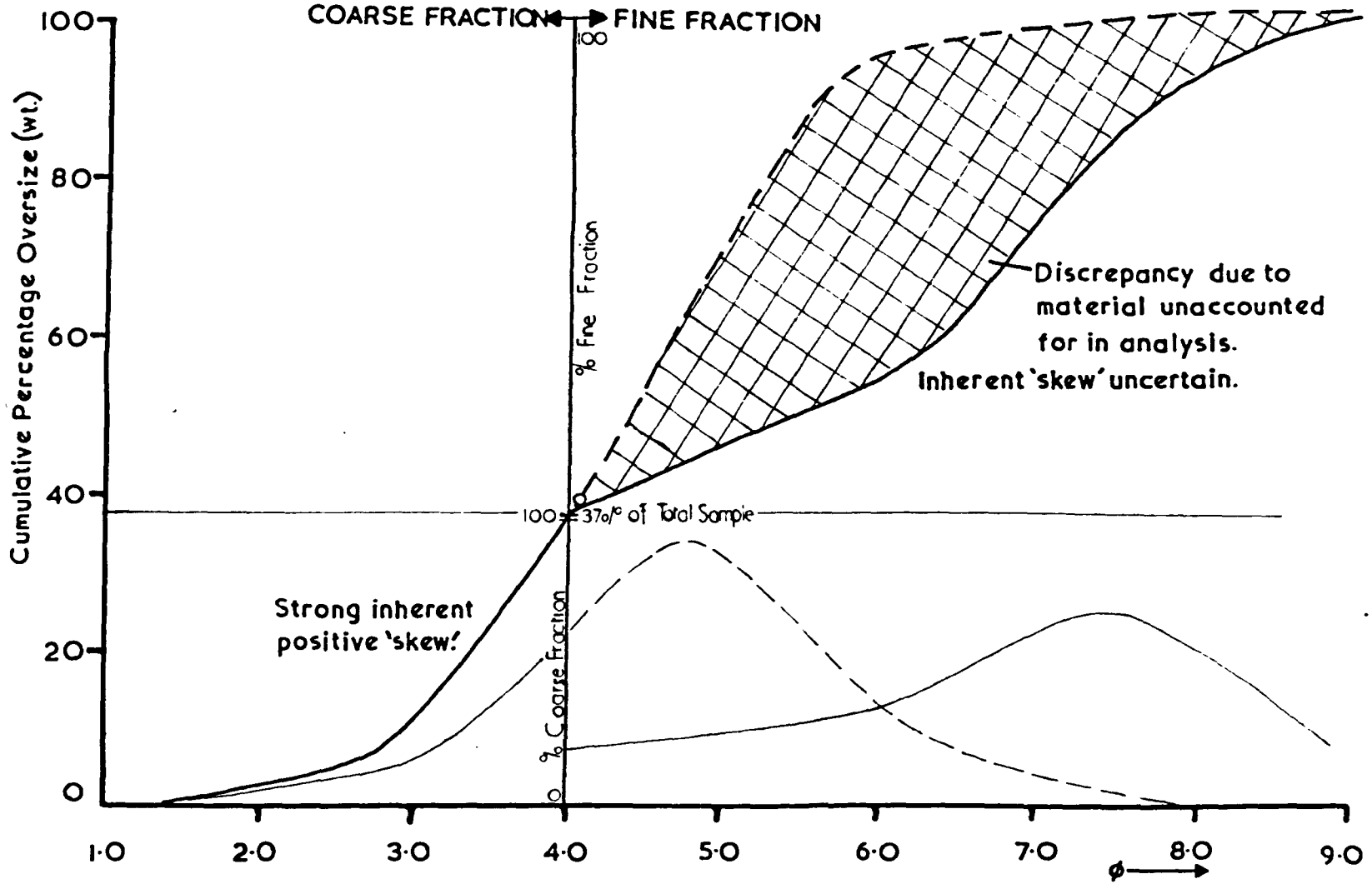


Figure 54a. Illustration of First Possible reason for Bimodality of Windermere Curves.

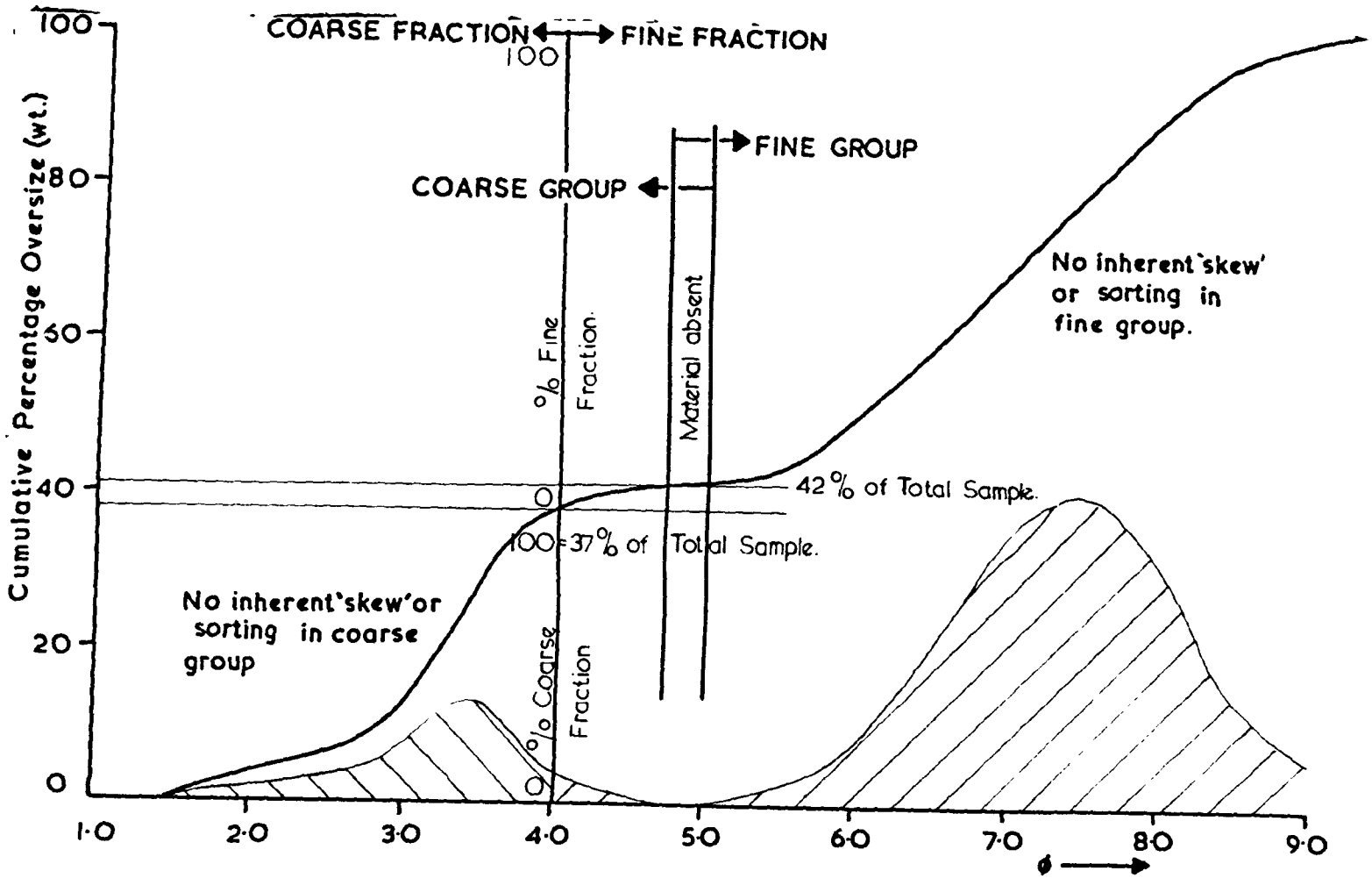


Figure 54b. Illustration of Second Possible Reason for Bimodality of Windermere Curves; also showing no overlap of groups; and illustrating the separate treatment of group data, not fractional data, showing lack of inher-ent statistical properties and difficulty of accurate distinction of groups.

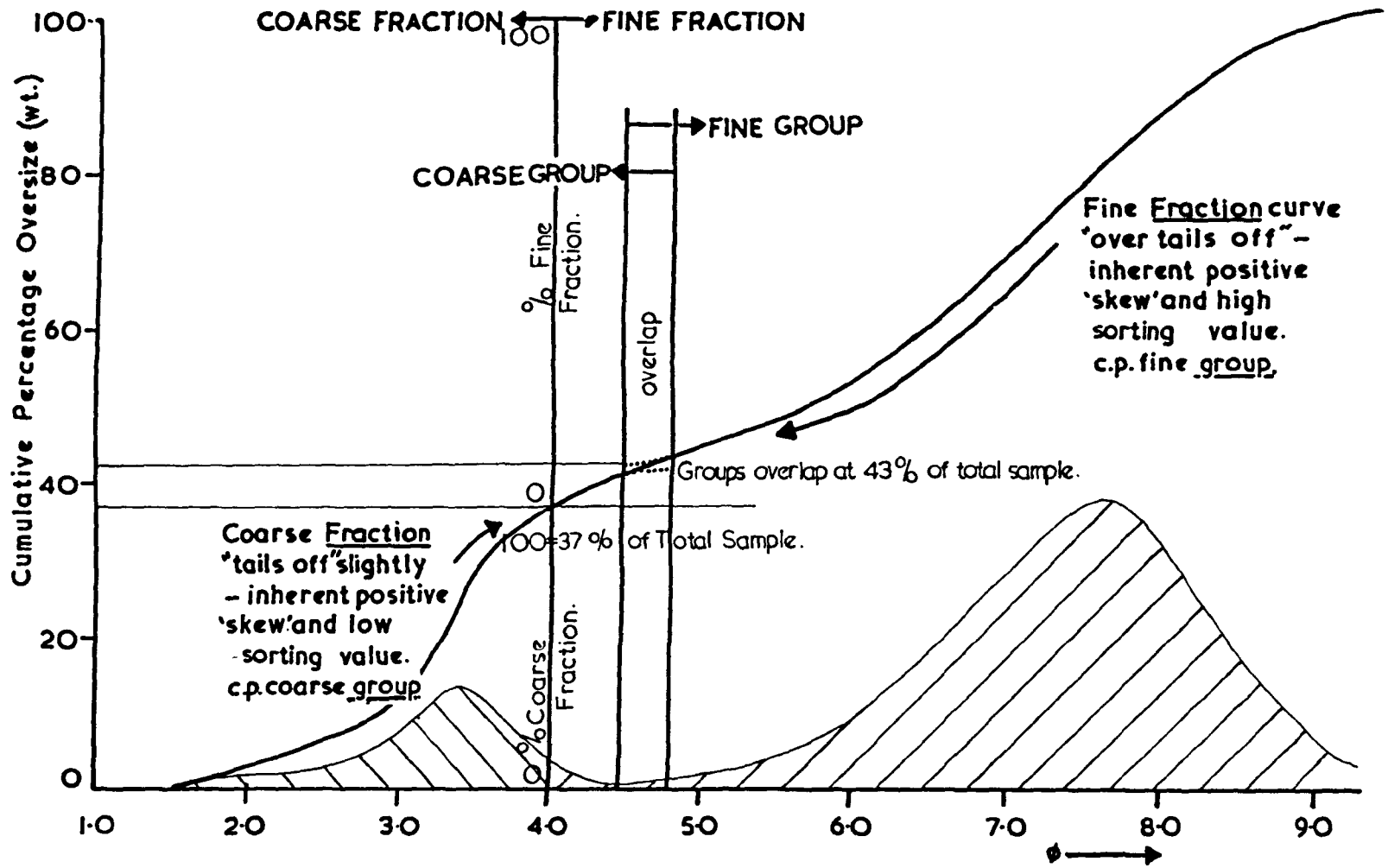


Figure 54c. Illustration of Second Possible Reason for Bimodality of Windermere Curves; also showing overlapping of groups; and illustrating the separate treatment of fractional data, not group data, showing inherent statistical properties and ease of accurate distinction of the fractions.

curves due to the nature of the "mixing". This aspect is not considered until Part III.

Combined curves of both particle size and settling rate distributions are bimodal but, in the surface ooze samples particularly, the settling rate curves show the effect less markedly. N.B. This is not the case with the curves on figures 47 and 48 because they were obtained from the same experiment and the same data.

A series of tests were devised to discover which of the possibilities is the true case:

a. A sample of diatomaceous cement (supplied with its unimodal size distribution curve) was analysed in the normal manner to discover whether the resulting curve was unimodal or not. The data are shown in table 25a and the curve in figure 55a . It proved to be unimodal (almost identical to the specification). Thus there was no material unaccounted for by the fine fraction analysis of this material.

b. Test sample no.2 was split into three portions in which the fine material analysed in the Sedimentation Balance had different upper size limits as follows:

i. Upper limit of fine material was 0.064 mm (Sieve Mesh 240), combined with a sieve analysis of material coarser than this to give a complete analysis (this is the normal case).

ii. Upper limit of fine material was 0.076 mm (Sieve 200).

iii. Upper limit of fine material was 0.104 mm (Sieve 150).

The flow sheet here is shown on figure 55b, data on table 25b.

The combined curves from these three tests (fig. 55c) show that the central point of inflexion has not effectively changed position in any of the curves. The curves for subsamples

Table 25. Tests for Bimodality.

a. Particle Size Analyses of Diatomaceous Cement.

Sieve Mesh No.	ø Values	Weight Percentage Oversize
85	2.42	0.2
100	2.65	1.6
150	3.25	24.1
200	3.65	41.0
240	3.90	48.3
	4.00	53.0
	4.50	76.5
	5.00	87.0
	5.50	91.5
	6.00	93.0
	7.00	95.0
	8.00	96.0
	9.00	97.0

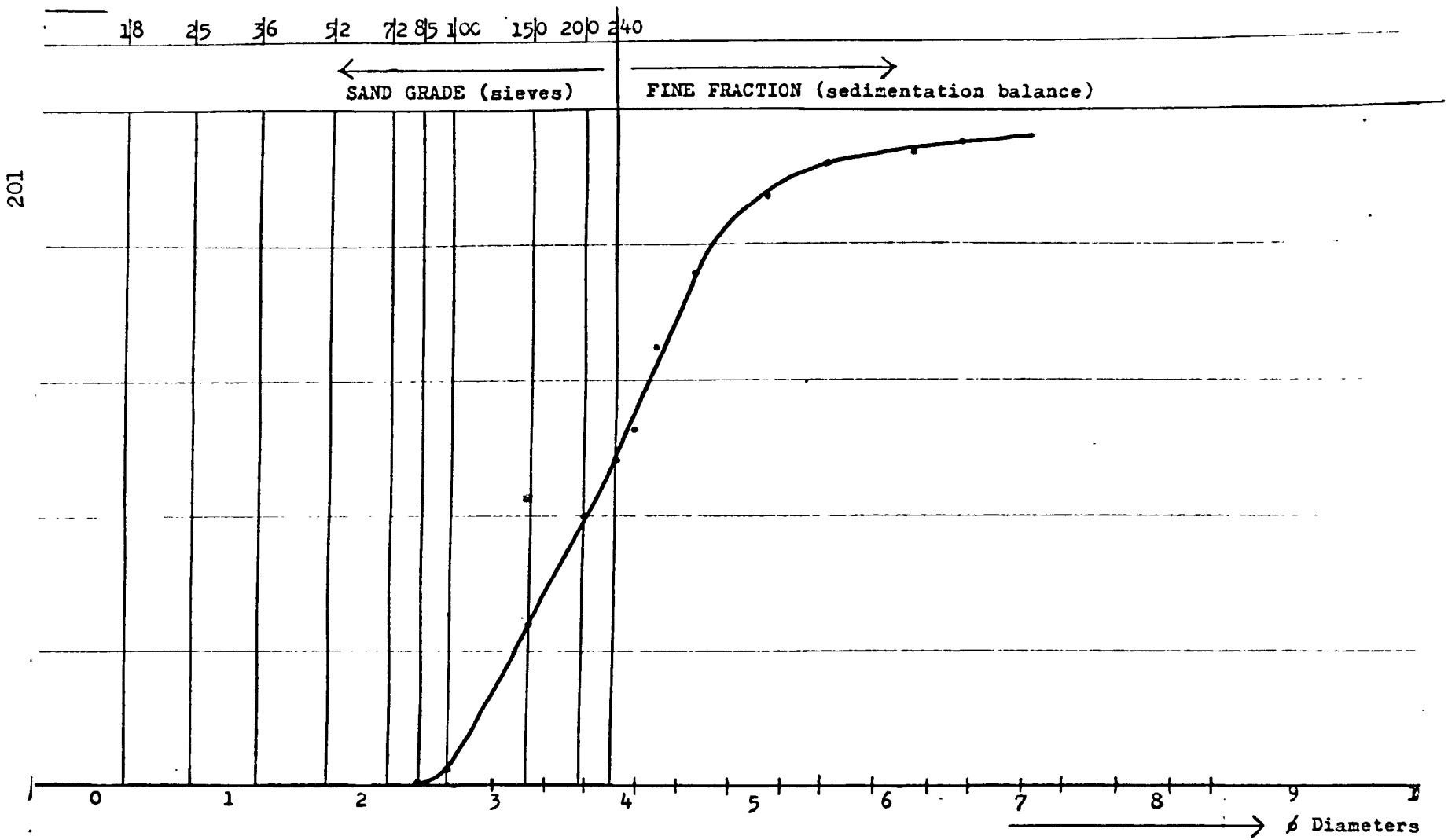


Figure 55a. Bimodality Tests with Diatomaceous Cement.

(Taken from table 25a)

Table 25. b. Particle Size Analyses of Test Sample II.

Sieve Mesh No.	ø Values	Weight Percentage Oversize		
		a	b	c
25	0.70	0.0	0.0	0.0
36	1.20	0.3	0.3	0.3
52	1.72	0.4	0.4	0.4
72	2.20	0.5	0.5	0.5
85	2.42	0.7	0.7	0.7
100	2.65	1.2	1.2	1.2
150	3.25	4.4	4.4	4.4
200	3.65	12.3	12.3	17.1
240	3.90	14.7	15.2	19.0
	4.00	14.7	15.8	20.0
	5.00	18.1	18.5	24.7
	6.00	30.5	28.9	37.0
	6.50	40.7	39.2	43.6
	7.00	54.3	53.5	53.4
	7.50	70.1	70.5	62.2
	8.00	88.0	88.7	73.8
	8.50	95.3	96.0	80.7
	9.00	98.7	98.8	87.5

N.B. The dotted lines indicate the sieved division between sand material and fine material for each subsample.

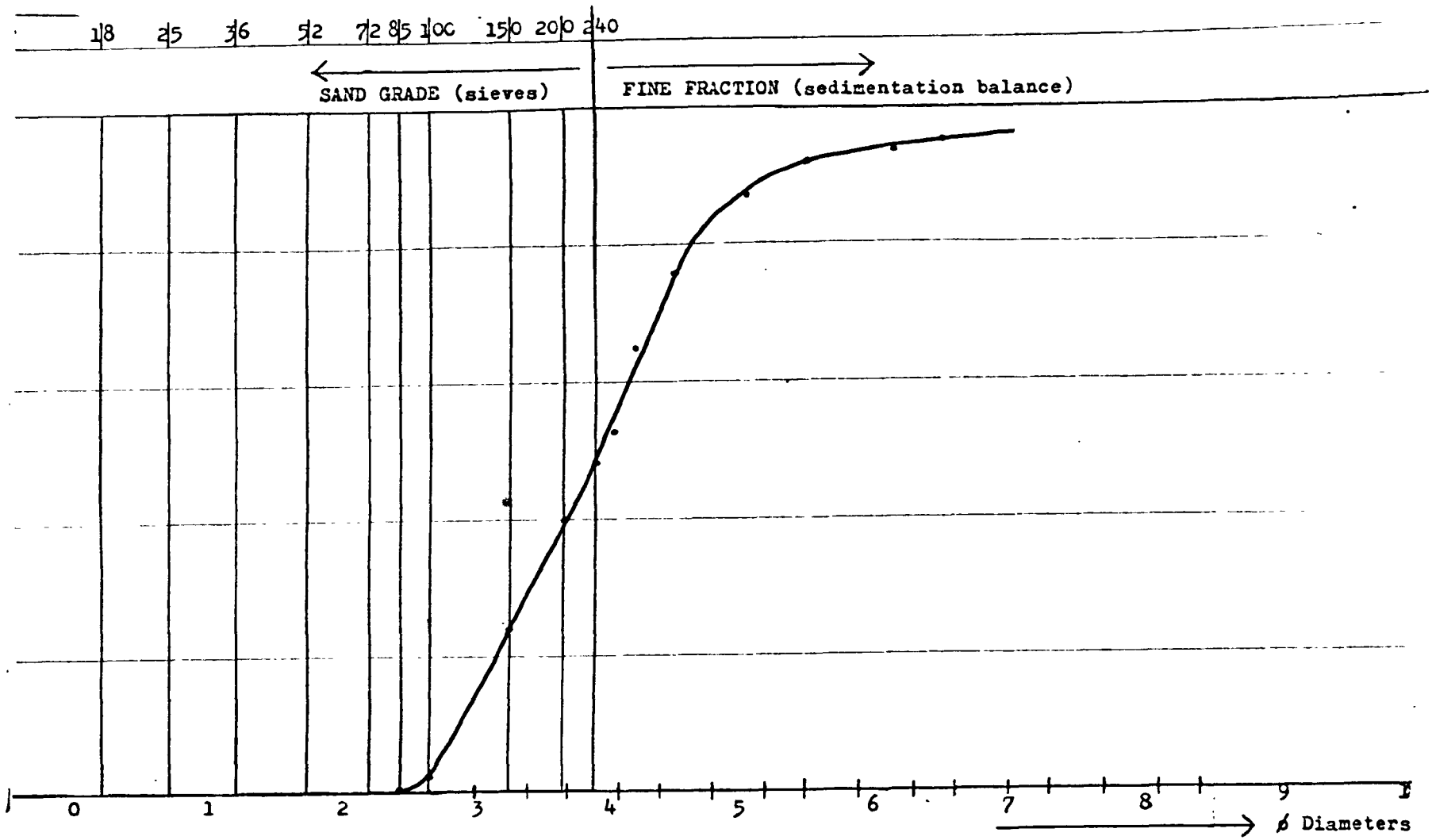


Figure 55a. Bimodality Tests with Diatomaceous Cement.

(Taken from table 25a)

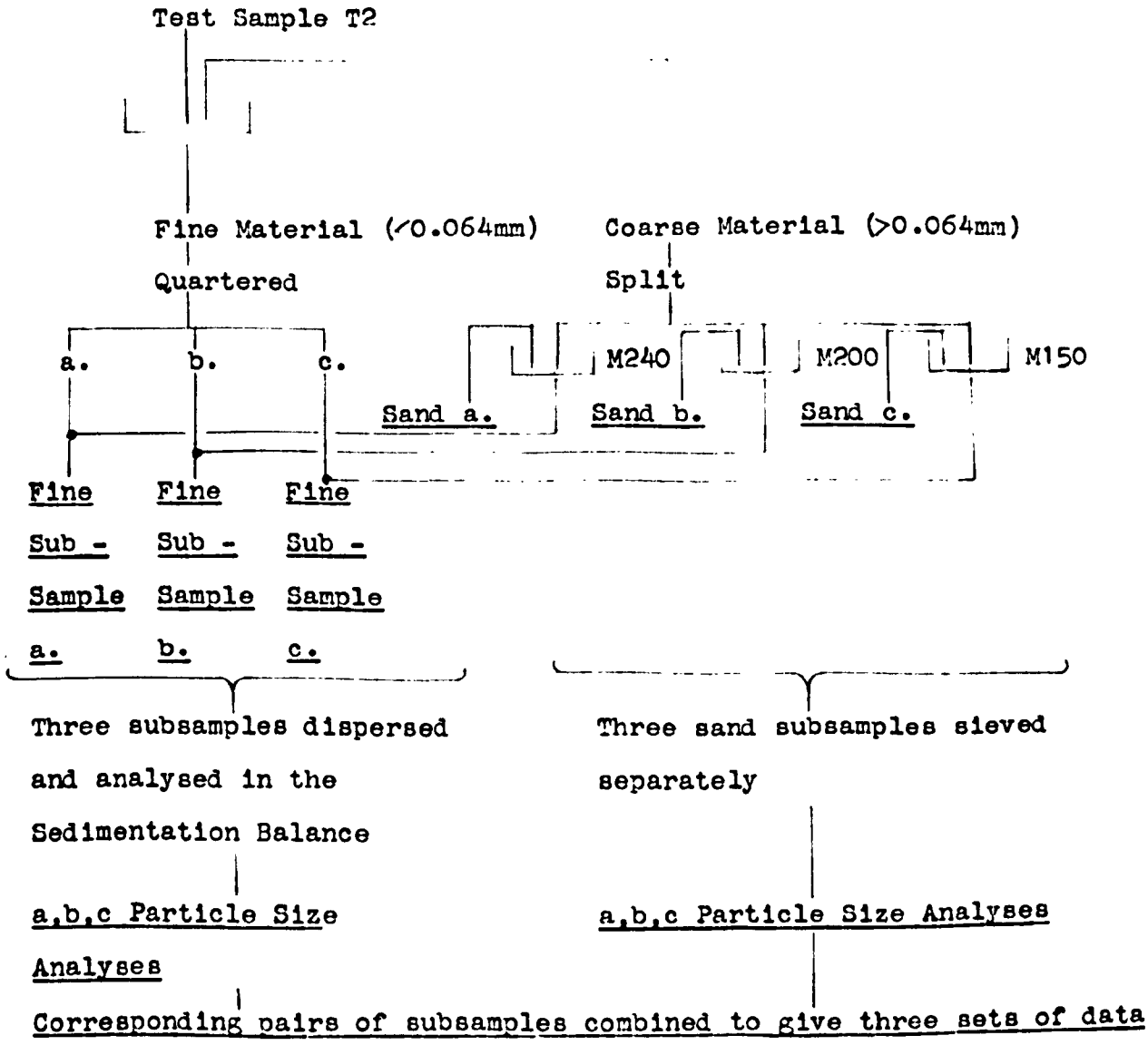


Figure 55b. Bimodal Test with T2 - Flow Sheet.

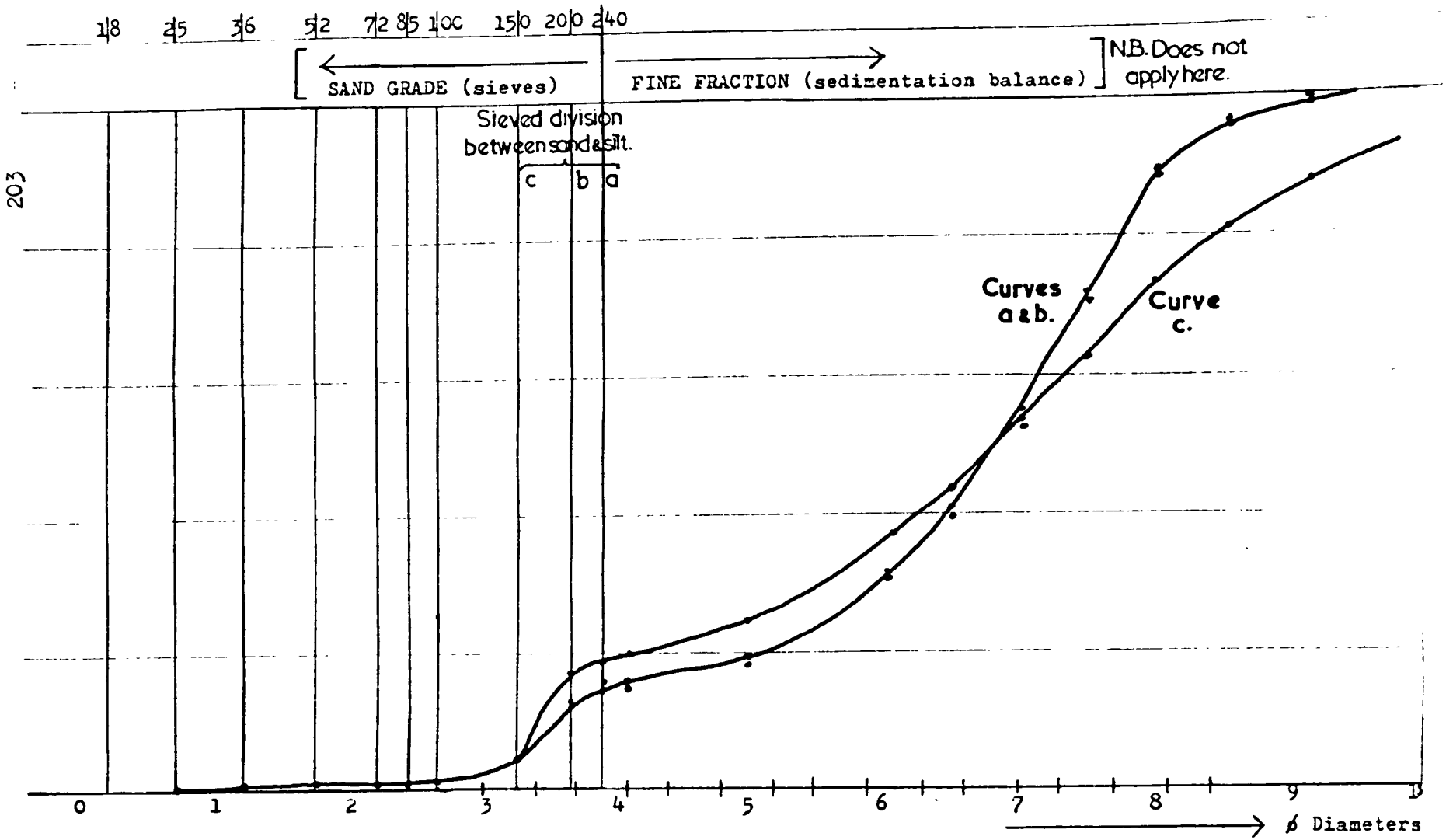


Figure 55c. Bimodality Tests with Test Sample No. 2.

(Taken from table 25b)

i and ii are similar to each other but the curve for subsample iii is seriously different. This deviation is thought to be due to the comparatively high proportion (10.3%) of sand material being analysed in the Sedimentation Balance, making initial readings highly susceptible to inaccuracy. This material (up to 0.104 mm) also grades slightly above the upper limit of accurate application of Stokes' Law.

Conclusions. The tests show that a truly unimodal sample gives a unimodal curve and that the distribution curve for test sample no. 2 is bimodal with the central point of inflexion between the groupsunchanged. Thus it is inferred that the distribution curves of most lake material are truly bimodal as examined in the laboratory, generally with a small amount of overlapping of the groups between ϕ4.0 and ϕ5.0 (0.062 and 0.031 mm).

Comparison Between Emery Tube and Sieve Results.

Emery (1938) claims that the settling method of sand analysis has the advantages of being quicker and more convenient than sieves and of accounting for the particles' S.G. and volume as well as size and shape; this latter makes it more "genetic". This should be of particular significance if it is true that a particle's settling velocity is closely related to the water velocity needed to raise it into stream suspension (Rubey, cited in Emery, loc. cit.). Emery admits that the reproducibility of sieve results is better than settling tube results. Poole et al (1951) showed that this deviation is not serious (1%) in fine sand but rapidly increases in coarser sands where sieves were found to be more accurate. Poole (1957) suggests that a number of sand particles settling together

interact physically and give spurious results: normal sand gave "coarser" results than the sieves by . 1/8 ϕ, heavy mineral sands by 1/2 ϕ (mica sands give similar medians but spurious sorting, skewness , and kurtosis). The author claims that the only satisfactory method would involve measuring the settling velocity of each particle separately, these behaved as expected. Folk (1962) claims that "sensitive" sand material properties such as skewness and kurtosis are best measured in the sieves because of the "heading", "tailing", and "eddying" phenomena in the settling tube. Hulsey (1961) has shown that the effects of these phenomena increase with sample weight to an optimum of between 3.5 and 4.5 gms.

In this initial study of the mechanical properties of sand grade material the coarse fractions were classified into four categories:

a. Organic matter absent, less than 10% of material coarser than Sieve Mesh 18.

b. Organic matter present, less than 10% of material coarser than Sieve Mesh 18.

c. Organic matter absent, more than 10% of material coarser than Sieve Mesh 18.

d. Organic matter present, more than 10% of material coarser than Sieve Mesh 18.

N.B. Material analysed in the Emery Tube is always finer than Mesh 18 (Chapter 9). Thus the curves of samples which contain material greater than this need to be extrapolated from the first co-ordinate down through the coarser grades. It is taken that the P90 ordinate is unaffected by this extrapolation if there is less than 10% material coarser than Mesh 18 (fig. 56).

Figure 17. Comparison of Emery Tube and Sieve results.

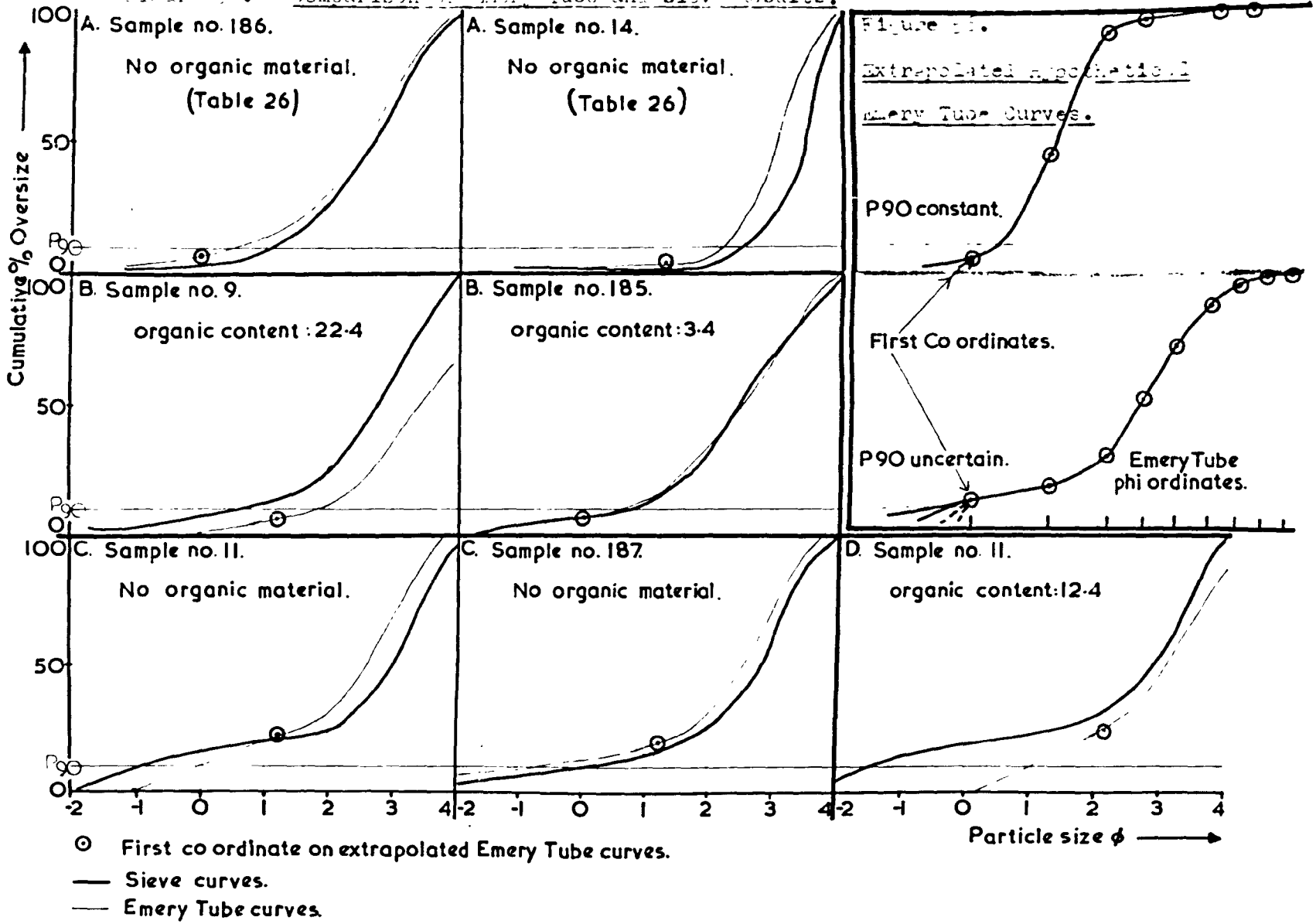


Figure 18.

Extrapolated hypothetical Emery Tube Curves.

In all these cases $\log_{10} v$ values were converted to phi values using Rubey's General Formula; the sieve and Emery Tube results were then plotted onto the same sheet of graph paper for easy visual comparison of the curves. Examples of a few samples in each of the four categories are shown in figure 57.

Category a.

Ooze sample nos. 9, 12, 13, 14; gyttja nos. 66, 67, 75, 81, 88, 89, 103; Late Glacial nos. 176, 177, 186; (all c and d analyses).

The Emery Tube curves are coarser than sieve curves in broad agreement with Poole (1957). However, the amount by which the medians of the two curves differed varied from sample to sample so that no single S.G. value would would have had any wider application than does 2.65. Thus it is especially important to recognise that Emery Tube medians are "hydraulic equivalents" for quartz spheres at 20°C. A detailed comparison of results is shown in table 26. The c and d analyses of sample no. 186, where MD (Sieve) = 0.158 mm and MD (Emery Tube) = 0.175 mm (deviation: 10% of MD Sieve; 11% of MD Emery Tube), are shown in figure 57. This comparison is the minimum of all the deviations discovered, the average is about 20%, approximately represented by sample no. 14, c and d analyses.

Category b.

Ooze sample nos. 9, 12, a and b analyses; Late Glacial no. 185, c and d analyses (grass roots comprised the organic matter in this sample)

The presence of organic matter reduces overall particle S.G. so that 3.4% organic matter in sample no. 185 makes the Emery Tube curve nearly coincident with the sieve curve and 22.4% in No. 9 brings it well to the fine side of the sieve curve.

Table 26. Comparison of Sieve and Emery Tube Data from Samples [illegible] Cat[illegible] A.

Sample No.	Sieves/Emery Tube	.D	SO		K	Kø
14	Sieves	0.100	1.21	(-)0.9[illegible]	.24	
	Emery Tube	0.122	1.30	(+)1.[illegible]	.31	0.31
13	Sieves	0.137	1.40	(+)1.0[illegible]	.26	
	Emery Tube	0.175	1.37	(+)1.04	.2	0.25
1	Sieves	0.120	1.27	(-)0.79	0.2	
	Emery Tube	0.135	1.30	(+)1.07	0.29	0.30
2	Sieves	0.141	1.38	(+)1.00	0.2(	
	Emery Tube	0.175	1.[illegible]	(+)1.04	0.24	[illegible]
9	Sieves	0.108	1.31	(+)1.04	0.21	
	Emery Tube	0.130	1.31	(+)1.12	0.21	0.23
186	Sieves	0.158	1.49	(+)1.08	0.20	0.20
	Emery Tube	0.175	1.53	(+)1.16	0.16	0.23
66	Sieves	0.125	1.36	(+)1.13	0.24	
	Emery Tube	0.140	1.37	(+)1.20	0.20	[illegible]
68	Sieves	0.098	1.21	(+)1.10	.22	
	Emery Tube	0.130	1.37	(+)1.00	0.19	.23
103	Sieves	0.115	1.30	(+)1.08	0.16	
	Emery Tube	0.130	1.40	(+)1.27	0.22	0.21
67	Sieves	0.117	1.30	(+)1.05	0.26	
	Emery Tube	0.155	1.29	(+)1.11	0.21	0.23
89	Sieves	0.105	1.23	(+)1.09	0.24	
	Emery Tube	0.117	1.28	(+)1.45	0.21	0.24
75	Sieves	0.130	1.36	(+)1.04	0.29	
	Emery Tube	0.170	1.40	(+)1.07	0.20	0.24
176	Sieves	0.095	1.15	(+)1.01	0.21	0.21
	Emery Tube	0.106	1.17	(+)1.10	0.19	0.21
177	Sieves	0.095	1.15	(+)1.01	0.21	0.23
	Emery Tube	0.108	1.17	(+)1.07	0.20	0.23

Category c.

Ooze sample no. 11; Late Glacial sample no. 187; (c, d analyses).

That part of the Emery Tube curve finer than Sieve Mesh 18 is on the coarse side of the sieve curve as expected. The P90 parameter, however, may be inaccurate. 11d and 187d show extreme possibilities for extrapolation.

Category d.

Ooze sample no. 11, a and b analyses; Late Glacial no. 189, c and d analyses.

These curves are liable to exhibit one or both of the discrepancies of categories b and c.

Conclusions.

a. Sand material which contains neither organic matter nor more than 10% greater than Sieve Mesh 18 give comparable curve shape results (table 26) in sieves and Emery Tube. The median result, however, is larger in the latter case, either because of a low choice of particle S.G. value (2.65) or because of the "mass interaction" of particles settling collect-ively (Poole, 1957).

b. The fact that organic matter affects both the operation and accuracy of the two methods of sand analysis makes it essential to denote the mechanical properties of the coarse material either from c or from d analyses.

c. The Emery tube method is similar to the Sedimentat-ion Balance in that it involves solid particles settling in a liquid medium and so the uncertainty of particle S.G. does not apply. For these reasons the settling data of the coarse material is preferred to the sieve data where possible.

d. Most of the Post Glacial organic lake samples (ooze and gyttja) contain fine sand material which was analysed in the Emery Tube. Certain ooze samples (no. 5), however, do contain a high proportion of gritty material and were analysed in the sieves. They were found to be badly sorted and polymodal, they were probably a result of gravel dropped off a dredging boat passing overhead.

e. Beach sands and Late Glacial deposits were always sieved, however, because many of them contained more than 10% material greater than Sieve Mesh 18.

f. Reproducibility of results, particularly curve shape, is more satisfactory in the sieves than in the Emery Tube (Folk, 1962). Pettijohn's statistical data, however, were used throughout for coarse and fine results in contrast to Folk.

g. An experiment was made adding 20% to the sieve size ordinates before calculating the statistical data. This was the average amount by which sieve curves were finer than settling curves and it had the effect of increasing the median value only, not the shape results. It proved to be unnecessary, however, because the value was only an approximate average and because the Emery Tube results are so closely comparable with the sedimentation results of the fine fraction (see above).

Comparison of a and c Analyses of Fine Material.

Richardson (1941) claims that the particle size results of the organic rich lake sediments are similar both before and after ignition; and that the organic matter, an important integral constituent, was not deposited as a mode separate to that of the mineral matter. In this study, there were comparisons made between results from dispersed suspensions

in the Sedimentation Balance before ignition and after ignition (a and c suspensions) of Sample nos. 9, 11, 12, 13, 14, 15, 16, 17 (ooze) and 81, 82, 83, 84, 86 (gyttja). The generalised com-parison is made on figure 58. Unlike Richardson's conclusion, the curves are not closely comparable in that the organic curve is finer than the other. This is probably because the particle S.G. value of 2.65 is seriously inaccurate for samples which contain about 20% organic matter, though it may be a fair approx-imation for the ignited material. The rapid "tailing off" of the a analysis curve, giving a very strong negative skew, may be due to colloidal material which remains in suspension indefinately. There is likely to be more of this in the organic suspension than in the other. However, the general conclusion that the organic matter does not occur as a separate mode does apply. The c analyses can therefore be taken as representative of sample particle size, more accurate than the a analyses due to the S.G. assumption.

Mechanical Analyses - Tabulated Results (Appendix No.4)

Ooze and gyttja are represented by c analyses after ignition, flocculation, Md/MD and grade mean. Sand is generally represented by settling data though occasionally by sieve data.

Beach sands are unimodal in that they contain no fine material. They are represented by sieve data.

Late Glacial material is represented by c analyses though not ignited, Md/MD and grade mean. Sand is always represen-ted by sieve data though by settling data as well, where poss-ible, for purposes of comparison with Post Glacial material.

Certain samples are unimodal extending into both fractions (near shore silt, lacustrine sand both Post Glacial and Late Glacial); these are represented by the appropriate data.

FINE FRACTION - GRAPH NOS. 2 a & b. SAMPLE SHEET NO.

WEIGHT PERCENTAGE OVERSIZE VS PHI DIAMETERS - (a) CUMULATIVE FREQUENCY CURVE

(b) SIMPLE SIZE FREQUENCY CURVE

(N.B. ALL PERCENTAGES ARE of FINE FRACTION ONLY)

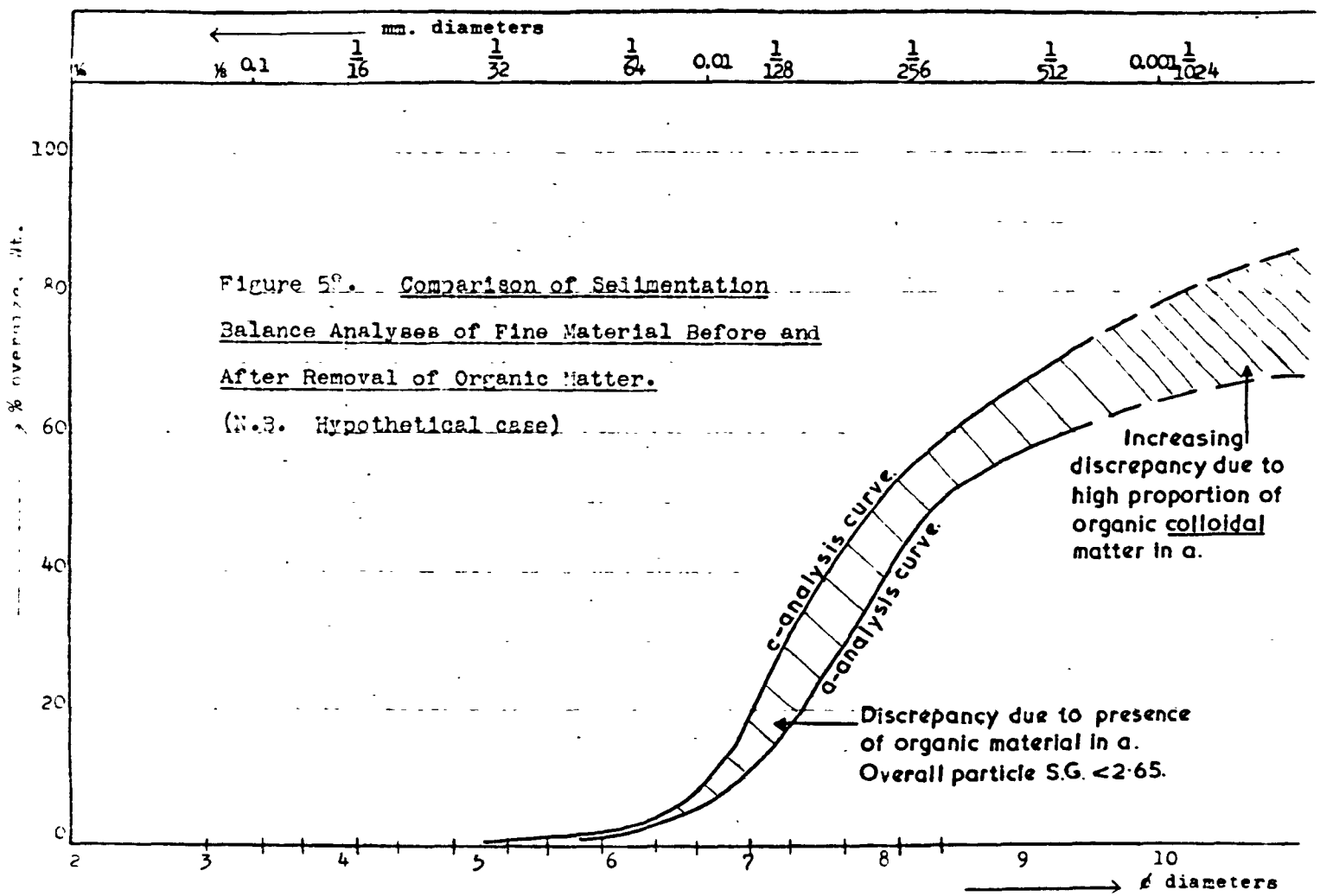


Figure 5. Comparison of Sedimentation Balance Analyses of Fine Material Before and After Removal of Organic Matter.

(N.B. Hypothetical case)

Chapter 16. Roundness Analyses.

(Krumbein and Pettijohn, 1938, Chapter 11;
Pettijohn, 1957, Chapter 2 .)

Preliminary Study.

No beach deposits had been sampled when this study was made. The first twenty two samples studied were used as tests (sample sheet nos. 1 - 22), they included organic lake deposits and shallow water clays. Coarse material was divided into four subgrades as follows:

a. Coarser than Sieve Mesh 25 (0.600 mm).
b. Coarser than Sieve Mesh 100(0.152 mm).
c. Coarser than Sieve Mesh 150(0.104 mm).
d. Coarser than Sieve Mesh 240(0.064 mm).

Small splits of material in subgrades b, c, and d were mounted onto graticule glass slides in the normal manner. Splits of material in subgrade a were mounted on Franke Trays and covered with cellophane because the grains were too large for normal mounting; the largest grains in subgrade a were studied by hand. Two hundred grains from each mount were counted by binocular and placed in five roundness categories as follows (fig. 59):

a. Angular; completely unworn by abrasion.
b. Sub-angular; arbitrary intermediate category.
c. Sub-rounded; arbitrary intermediate category.
d. Rounded; arbitrary intermediate category.
e. Well rounded; completely rounded due to abrasion.

Only the sharpest corner or edge of the grain was studied in each case to minimise human error. This feature is the most relevant that is easily studied with respect to the degree of abrasion

Figure 59. Roundness Categories.

(Reproduced from Russell and Taylor, 1937)

Magnified 8.5 times.

undergone by the grain (Russell and Taylor, 1937). Roundness was not studied in great detail either by considering all the corners and edges (Robson, 1958) or by considering more than five roundness categories (Powers, 1953). It is emphasised that the degree of roundness is being studied as a guide to the abrasion undergone by Windermere material; rather than the degree of sphericity, a property related to the state of the parent rocks. For example, in category e (well rounded) the particles are perfectly smooth, not necessarily perfectly spherical.

Quantitative studies were done as follows: each grain was placed in its roundness category and counted on the Point Counter. The number of grains in each category was multiplied by an arbitrary number corresponding to that category.
angular x 1; sub-angular x 2; sub-rounded x 3; rounded x 4; well rounded x 5.
The five resulting figures were added and divided by the number of grains counted (200 here) to give the "Roundness No". of that mount. This is an average roundness for the grains counted in that subgrade. For example, a roundness no. of 2.51 implies that the average roundness of the grains counted is just over half way between being sub-angular and sub-rounded. The roundness no. given by a count of two hundred grains was found to give an average value sufficiently reproducible for present purposes. There were likely to be four roundness nos. in each sample; these were averaged taking into account the percentage by weight of the total coarse fraction in each subgrade. This final average is known as the "Weighted Mean" and was given as the roundness value of each sample studied. This method of calculating the degree of roundness is described by Russell and Taylor (1937).

The data for the preliminary samples are listed in table 27. Graphs were plotted of roundness no. against ø diameters (the latter was the minimum particle diameter in each subgrade), the curves are shown in figure 60 and grade down from about 1.90 along the ø0.70 axis to 1.60, 1.50, and 1.45 along the ø2.65, ø3.25, and ø3.90 axes respectively. The roundness nos. do not become distinctive until the coarser grades. It is not certain whether the apparent randomness of roundness nos. in the three finest grades was due to the counting technique and difficulties in making fine distinctions of very small grains, or not.

Conclusions of Preliminary Study.

a. Abrasion effectively increases sharply with the size of particles larger than about 0.150 mm. Grains smaller than this vary apparently randomly between 1.40 and 1.70.

b. All grains should have roundness nos. of 1 if not rounded at all. It is not therefore certain whether the rounding of small grains is, in fact, related to that of the large grains or whether the parent material is already slightly rounded.

c. This study tends to support Russell and Taylor (1937, p. 251) in saying that roundness studies should be confined to material larger than 2.00 mm ("pebbles").

d. Weighted means of the preliminary samples were unlikely to be of any significance and were not considered.

Standardised Procedure for the Main Study.

Material larger than Sieve Mesh 8 is divided into the two following fractions:

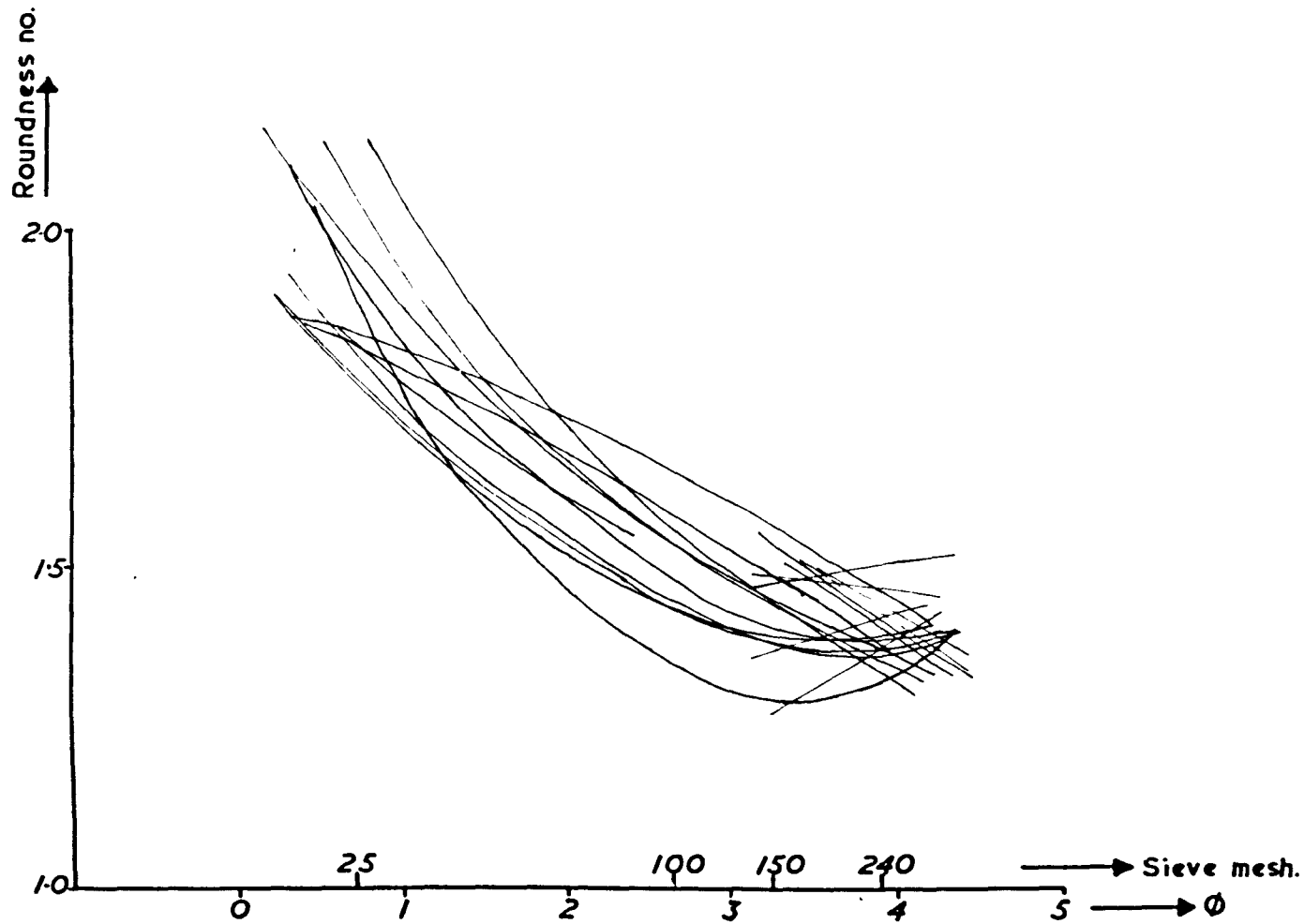
Table 27. Preliminary Roundness Analyses.

Roundness Numbers.

Sample No.	Sub-Grade 1	Sub-Grade 2	Sub-Grade 3	Sub-Grade 4
13	1.85	1.53	1.57	1.47
83		1.51	1.51	1.43
15	2.17	1.69	1.45	1.36
14		1.50	1.31	1.42
13	1.76	1.58	1.42	1.46
82		1.66	1.53	1.46
81		1.57	1.51	1.50
11	2.00	1.55	1.50	1.51
12		1.61	1.49	1.42
86	1.79	1.49	1.39	1.41
85		1.47	1.48	1.38
17	1.81	1.63	1.51	1.39
9		1.50	1.48	1.42
103	2.00	1.49	1.48	1.42
187	2.10	1.54	1.47	1.44
186	1.95	1.45	1.41	1.39
202	1.89	1.43	1.30	1.34
185	1.84	1.50	1.49	1.35
205		1.48	1.41	1.47
198		1.47	1.50	1.43
206	1.91	1.48	1.43	1.40
189	1.78	1.47	1.38	1.40

Figure 60. Preliminary Roundness Tests - Sieve Grades vs Roundness Numbers.

(Taken from table 27)



a. Larger than Sieve Mesh 5 (3.00 mm).

b. Larger than Sieve Mesh 8 (2.00 - 3.00 mm).

The percentage of each of these subgrades of the total weight larger than 2.00 mm is determined. Two hundred grains in each subgrade are counted for roundness individually by hand. Roundness nos. are calculated and averaged appropriately to give the weighted means.

Lake sediments, apart from the pebble layers in the Late Glacial, do not contain material larger than 2.00 mm in sufficient proportion for roundness analyses. This type of analysis is therefore most useful for studying the different abrasion on the various beaches around the lake and for comparing roundness of boulder clay material, other Late Glacial material, and Post Glacial material.

Many of the samples studied did not contain sufficient material for two hundred grains in each subgrade to be counted; these may not be strictly comparable with the others. Otherwise the reproducibility of results obtained by one operator was tested and found to be satisfactory.

PART IIC. VISUAL, GRAPHICAL , AND STATISTICAL METHODS OF REDUCING DATA TO A MANAGEABLE STATE AND OF EXAMINING THE RESULTS.

Chapter 17. Environments of Deposition of Material Sampled.

It was discovered that the cataloguing of samples as outlined in Part IIA, though accurate when used by itself, placed inherent limitations on the examination of genetic relat--ionships between deposits on a basis of sedimentary environments. The three sections of this chapter are devoted to outlining the methods by which a genetic classification is obtained of the Late Quaternary Windermere samples examined during this study. Visual field and laboratory methods are included here as well as the statistical methods. The first two sections are devoted to the classification of Late Glacial samples for cataloguing purposes (the categories decided upon in these sections were used in the catalogue, table 5). The third section describes the method for classifying all the samples, Post Glacial and Late Glacial alike. Some parts of the three sections are repetitive of earlier sections of the thesis but they follow a logical order to the conclusions of the chapter.

Distinction of Boulder Clay from Post Boulder Clay Late Glacial Deposits.

The distinction between boulder clay and fluvioglacial clay often cannot be made in the field but the degree of sort--ing (SO) of the coarse material (>0.064 mm), sieved out of these deposits and examined in the laboratory, is used instead. A total of thirty nine samples of Late Glacial material were collected by the present author either from the shoreline of the lake or in the surface sampler from the shallow "threshold" region (Nos. 185 to 223). Thirty one of these yielded more than 5% larger than 0.064 mm and thus gave coarse fraction analyses.

These sieve curves fell into two immediately distinguished categ--ories: a. Unimodal, simple distributions for aqueous sediments.

b. Polymodal with high kurtosis, complex, non aqueous.

These are shown in figure 61a; for a similar comparison see the curves drawn from Udden's data in Hatch et al (1957, fig. 8, p. 70) SO was calculated for thirty of these samples. One of the complex curves (No. 218) was polymodal to the extent that sorting was of no significance (the rest of the curves in this category were poly--modal, but SO was calculated for purposes of distinction). The SO values were plotted on a linear diagram and found to be divided into "sorted" ($SO < 3.0$) and "unsorted" ($SO > 3.0$) categories which exactly corresponded to the normal unimodal and non normal polymodal categories respectively, as shown in figure 61b. The former "sorted" twenty samples were termed "post boulder clay Late Glacial deposits", the latter "unsorted" five samples "boulder clay" (Wright, 1937; Charlesworth, 1957; Holmes, 1944, p.226). Seven of the eight remaining samples (Nos. 188, 190, 202, 203, 204 205, 206), which had not been analysed in this respect, were surf--ace samples of which all the others (Nos. 185, 186, 187, 189, 207 208) were in the sorted category. These were therefore classified as post boulder clay Late Glacial deposits; so was the other one (No. 211) which was a clay in the special "deltaic" sequences found at Brathay and Troutbeck.

Samples were catalogued after this examination: nos. 185 to 217 are post boulder clay Late Glacial deposits, and nos. 218 to 223 are boulder clay.

Initial Subdivision of Post Boulder Clay Late Glacial Deposits.

These include surface and shoreline samples as well as

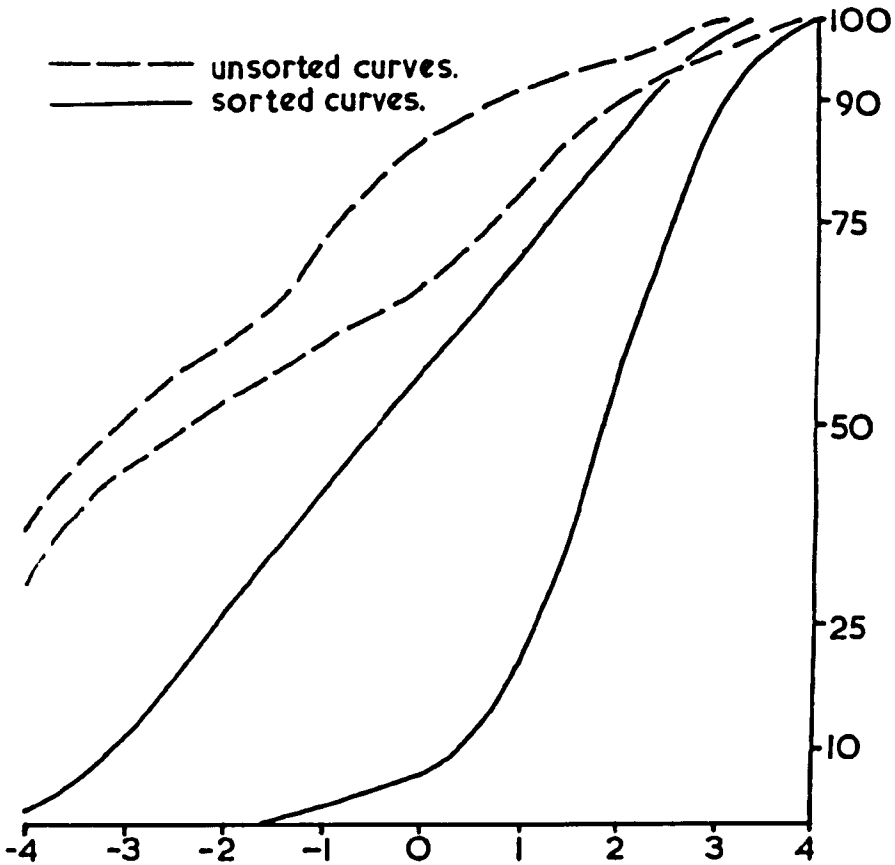
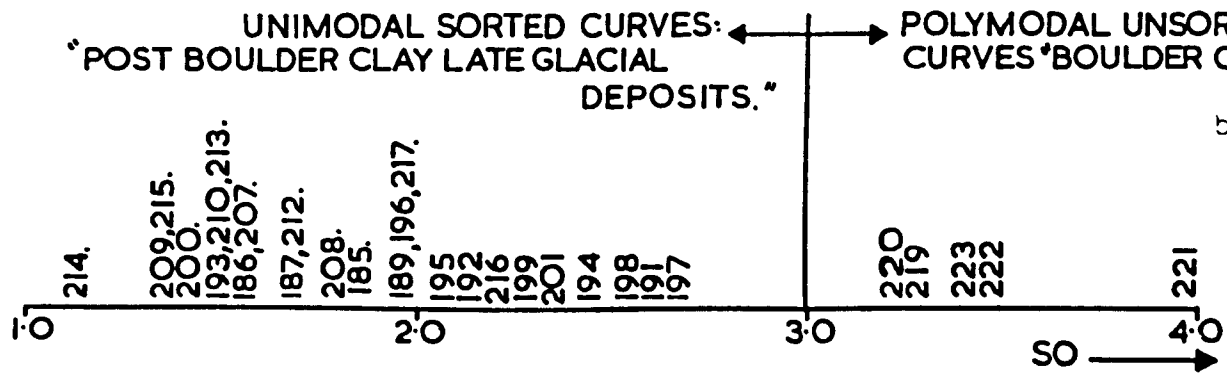


Figure 61. Sieve Data of Late Glacial Shoreline and Surface Samples.

a. Generalised Curves.



b. SO - Values.

core samples from water deeper than 20 metres. Three main categories were distinguished as well as further subdivisions of each:

a. "Lacustrine" Deposits from the cores (Nos. 145 to 184). Late Glacial deposits in the main lake were subdivided visually when the cores were unwrapped and scraped in the laboratory; samples were taken only where there was a distinctive and practic--able thickness of the appropriate facies; narrow clay/silt varves were not differentiated intentionally. There were three main sub--divisions: Pink Plastic Clay (Nos. 145 to 165); Dark Grey Semi-Plastic Silt (Nos. 166 to 173); and Light Grey Friable Sand (Nos. 174 to 178). Also certain samples in some of the cores contained proportions of rafted pebbles, these were sieved out with Mesh 240 and analysed as separate samples; this process was justified bec--ause none of the other clay or silt samples contained any material greater than 0.064 mm. Thus clay samples 145, 146, 148, 154, 161, and silt sample 172 contained these Pebble Bands (Nos. 179 to 184)

b. "Deltaic" Deposits from the special glaciolacustrine (ponded) sequences of strata found under the flat lying regions near the larger rivers' mouths at Brathay and Troutbeck (Nos. 211 to 217). The sequence is explained in Chapter 1 and illustrated in both the Appendix, fig. id, insets nos. 2 and 3, and the next section. Subdivisions were made in the field: Pale Clay (Nos. 211, 212) is the lowest visible facies in the sequence; it is over--lain by Dark Grey Silt (Nos. 213 to 217) which contains some pebbles, particularly at Brathay. The boundary is sharp at Trout--beck and only fairly sharp at Brathay.

c. Fluvioglacial Deposits (Nos. 185 to 210) is a general term used here for all Late Glacial material other than boulder

clay, lacustrine, or deltaic deposits. They were formed in and around small temporary streams and lakes resulting from the melt--water conditions after the ice had started to retreat, when some had melted and some remained stagnant. They are distinguished genetically from boulder clay in that they are among the first generations of deposits derived from the drift by aqueous erosion, transport, and deposition, resulting in some degree of sorting (Chapter 1). In this respect lacustrine and deltaic deposits are fluvioglacial but they were kept separate here for convenience. The subdivisions were made visually. Rusty Clays (Nos. 185 to 190) overlie smoother clays in the surface sample short cores. They are thought to be a result of the special conditions where wave action oxygenates the shallow lake floor near the islands so that grass and weeds take root in the clay as if it were soil; the top few inches are turned to the rusty colour and the clay minerals are altered (Chapter 30). Two Late Glacial Sands (Nos. 209, 210) were distinguished, without significant matrix. One of them was semi-consolidated and rusty coloured; it overlay a pale clay at Cock--shott Point and was part of a complex sequence of laminated silts and clays (current bedded); the cause of the rusty colour and the consolidated state of the sand is not understood. The rest of the Late Glacial samples were termed Clays (Nos. 191 to 208) and catalogued together for convenience.

The following section includes further subdivisions of Late Glacial material relating these deposits more closely to their environments of deposition and to those formed in the Post Glacial period.

Triangular Scatter Diagram Based on Particle Size Grades.

The diagram (fig. 62a) has as its three apices, 100% sand grade (>0.064 mm), 100% silt grade (0.0020 to 0.064 mm), and 100% clay grade (<0.0020 mm); a full statistical explanation is found in Chapter 18. All the samples analysed in this study were plot-ted inside the triangular diagram as shown, except beach sands and lacustrine rafted pebbles (100% > 0.064 mm; Nos. 42 to 65 and 179 to 184 respectively); "coke" layers in the Post Glacial gyttja sequence in which the origin of the coke is problematic (Nos. 140, 141); and Pink's soil, boulder clay, and rock samples (Nos. 224 to 272, used only for qualitative analyses). The groupings which are superimposed on the diagram are arbitrary but they appear to be relevant to a genetic classification of Late Quaternary material in the basin.

Theoretical Considerations.

It is important to discuss the general significance of a diagram of this type with respect to the transport and deposition of aqueous sediments. First, deposition by moving water tends to lay down coarser material first or, generally, in the order sand - silt - clay. Second, single phase deposition by moving water tends to produce a sediment with a unimodal settling velocity distribution (often equivalent to particle size), so that settling velocity bimodality is an indication either of more than one phase of deposition or, possibly, of subsequent redistribution (Pettijohn, 1957, Chapter 2). Thus the points on the scatter diagram of simple aqueous sediments would be expected to concentrate along the two sides of the triangle, sand - silt and silt - clay, with clay being eliminated towards the sand apex and vice versa. Figure 62b shows this by a series of zones of hypothetically decreasing point density. It should be noted that this diagram is

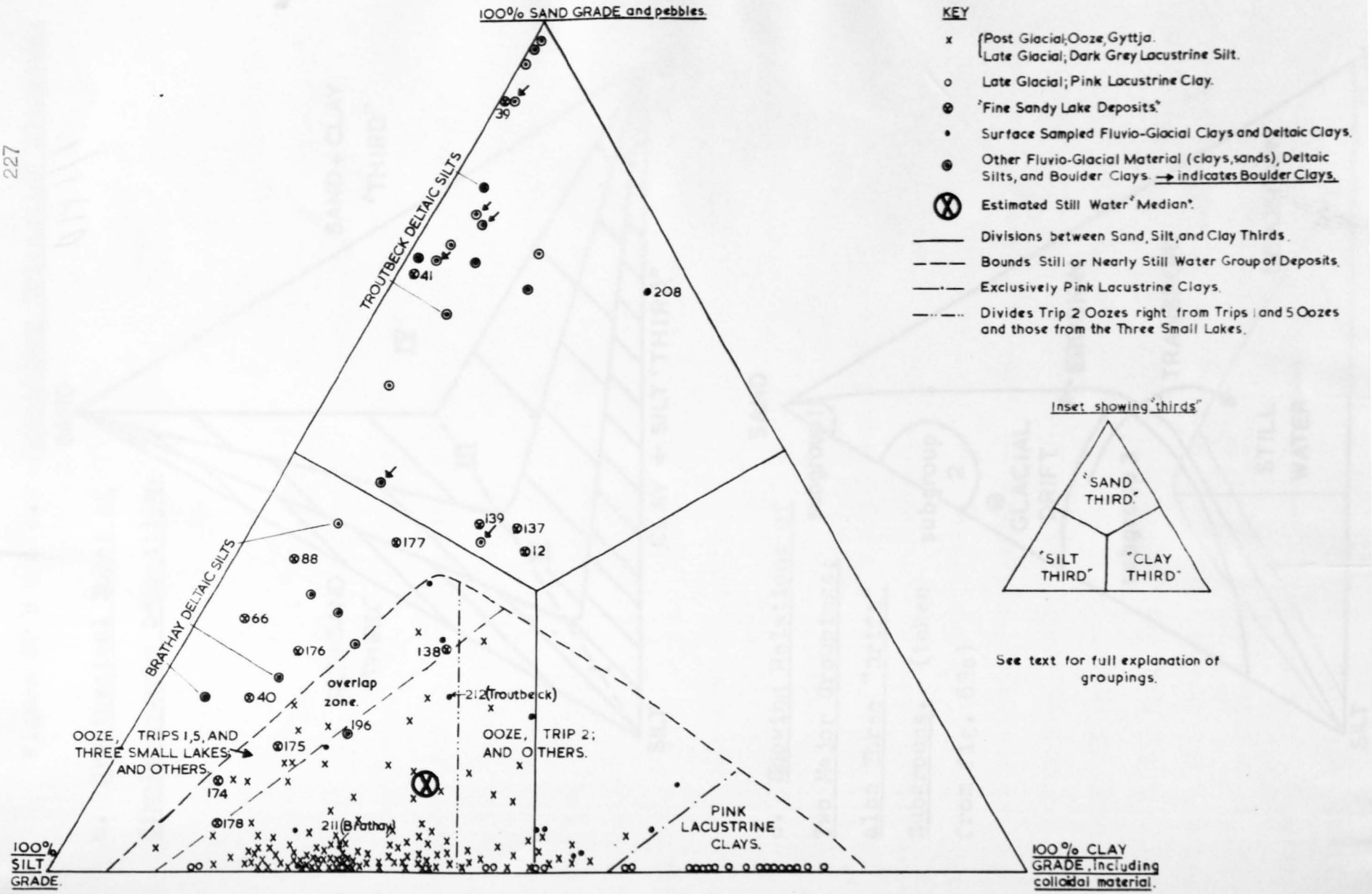
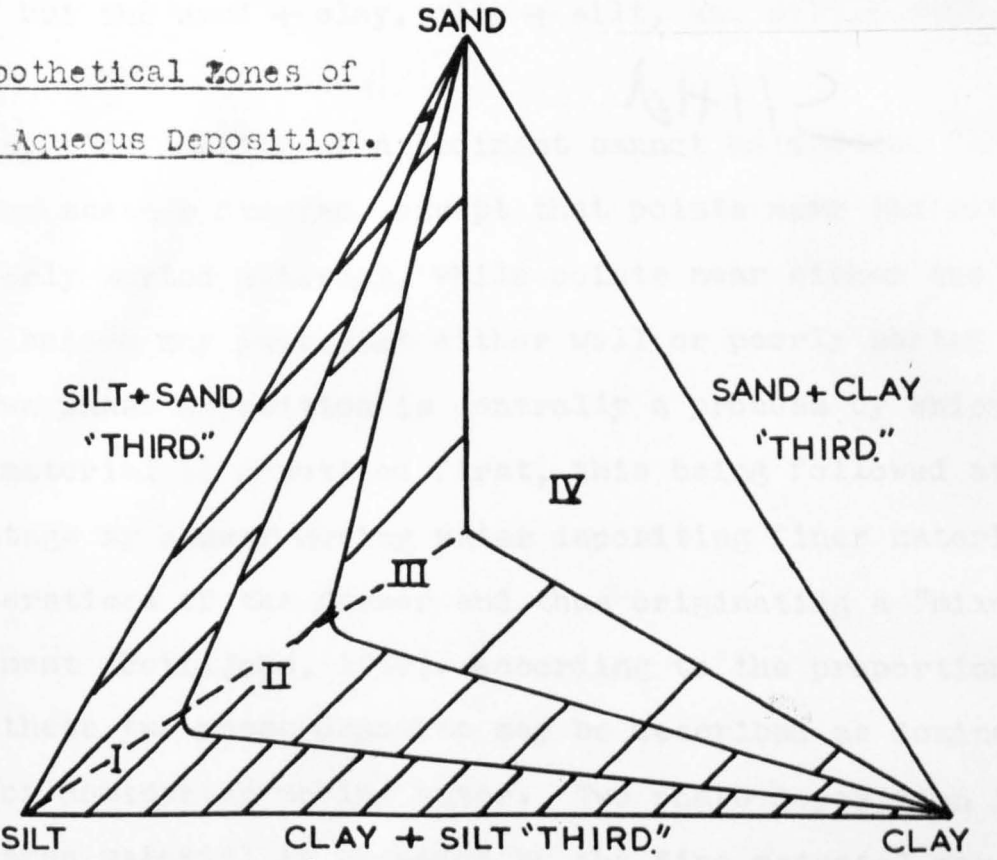


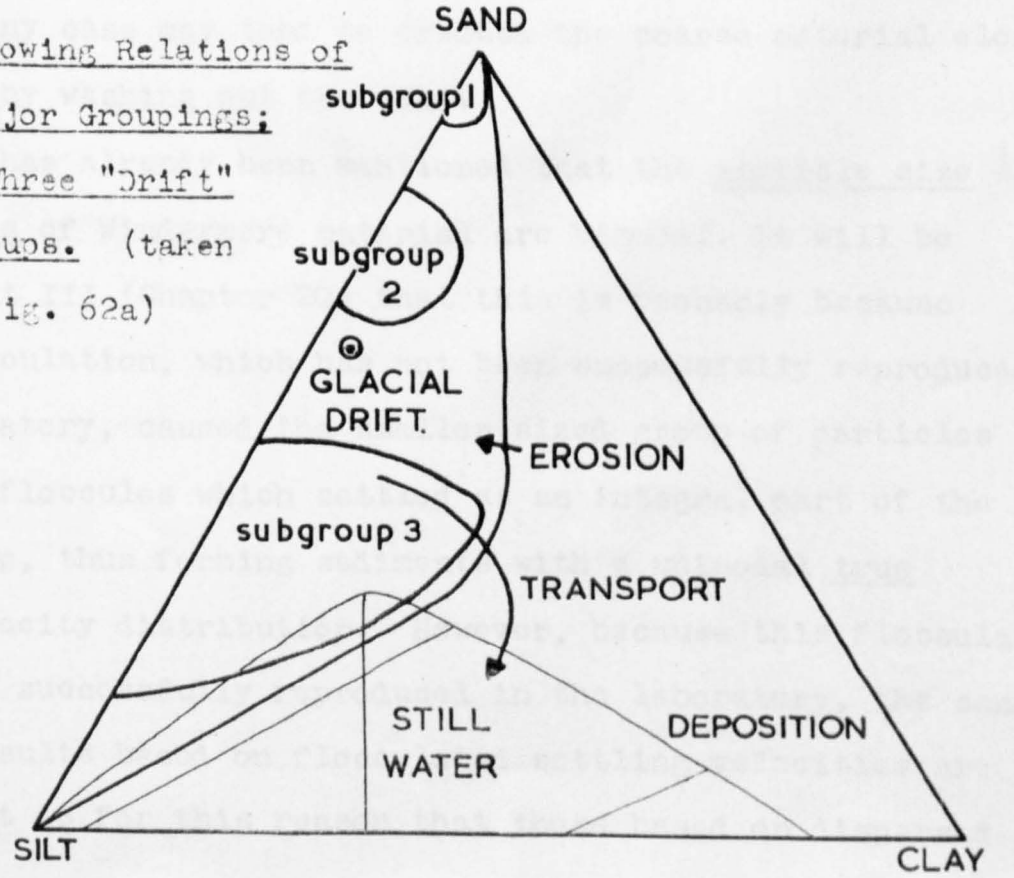
Figure 62a. Triangular Scatter Diagram with Still Water Grouping and Subdivisions.

Figure 62 b and c. Subsidiary Triangular Diagrams.

b. Hypothetical Zones of Simple Aqueous Deposition.



c. Showing Relations of Two Major Groupings; also Three "Drift" Subgroups. (taken from fig. 62a)



based on the three thirds of the triangle; not sand, silt, and clay thirds; but the sand + clay, clay + silt, and silt + sand thirds.

Complications. The sorting of a sediment cannot be deduced from the triangular scatter diagram except that points near the centre represent poorly sorted material, while points near either the edges or the apices may represent either well or poorly sorted material. Two phase deposition is generally a process by which the coarser material is deposited first, this being followed at some later stage by slower moving water depositing finer material into the interstices of the former and thus originating a "mixed" bimodal sediment (Pettijohn, 1957). According to the proportions of the two, these two phase deposits may be described as dominantly still water or dominantly moving water. Two phase deposition in which the coarse material is preceded by the fine material may occur, but the process is more complex (loc. cit.). Subsequent erosion in any case may tend to produce the coarse material alone (100% sand) by washing out the fine.

It has already been mentioned that the particle size distributions of Windermere material are bimodal. It will be shown in Part III (Chapter 20) that this is probably because natural flocculation, which has not been successfully reproduced in the laboratory, caused the smaller sized group of particles to form larger floccules which settled as an integral part of the coarser group, thus forming sediments with a unimodal true settling velocity distribution. However, because this flocculation has not been successfully reproduced in the laboratory, the sand/silt/clay results based on flocculated settling velocities are uncertain. It is for this reason that those based on dispersed

settling velocity (equals particle size here) are used instead. It is likely that flocculation does not occur until the aqueous environment is comparatively still, because faster moving water would tend to inhibit physically the formation of floccules. If so, this would allow the assumption that the combined genetic (transport and depositional) implications from the diagram are little altered from the true case.

The sand and pebbles apex is a possible source of mis-interpretation. It includes all material greater than 0.064 mm ranging, in effect, from fine sand up to coarse pebbles of 50 mm or more in diameter. The coarse sand and pebbles always occur as a separate mechanical (particle size) population from the fine sand-silt - clay "mixtures" mentioned above (this agrees with Spencer, 1963). For this reason the Late Glacial coarse sandy and pebbly samples and the subgroupings of their points are discussed and illustrated separately from the more important and numerous finer samples. An example of the possible misinterpretation is the prox-imity of the sample point of No. 39 (near shore silt) to one of a boulder clay.

General Discussion of Figure 62a.

The most striking feature of the large scatter diagram is the fact that points are concentrated into the equivalent of zone I (fig. 62b). Approximate concentrations:

Zone I: 85%.

Zone II: 10%.

Zone III: 4.5%.

Zone IV: 0.5%.

The two major groupings appear to "wedge into" the silt apex in the same manner as do the clay + silt and silt + sand thirds on

hypothetical figure 62b; the actual case is shown on figure 62c. The groupings are termed "still water" (eqivalent to the clay + silt third) and "glacial drift" (equivalent to silt + sand). The boulder clay part of the drift, before redistribution, was non aqueous and its points would probably be scattered randomly all over the triangle. The present scatter suggests that aqueous erosion of this drift has washed out the fine material (fine silt and clay) into the "still water" grouping, thus moving the previous random drift grouping into the coarse silt and clay third (or present "glacial drift" grouping). This phenomenon may be common in lakes where the bottom sediments are derived from drift material.

The two major groupings are discussed in detail in the following sections.

Major Still Water Grouping.

The more important of the two groupings superimposed on the triangular scatter diagram as shown is based on (grouped around) the visually distinctive facies known to have been deposited in a lake, Windermere itself, Grasmere, Rydal Water, or Elterwater. This group is termed, for convenience, the "still water grouping" and its main concentration of points tends to follow the clay silt edge of the diagram. It is grouped around the points of surface ooze (Nos. 1 to 38), gyttja(Nos. 66 to 136), and Late Glacial lacustrine material including pink clay bands in gyttja (Nos. 142 to 178). It <u>includes</u> all samples in these categories <u>except</u> a small group termed the "fine sandy lake deposits".

<u>Fine Sandy Lake Deposits.</u> Most of the sample points of these deposits occur outside the still water grouping though four of them (sand in gyttja no. 138, sand in Late Glacial material nos. 174, 175, 178) occured in that zone on the upper left hand end of the major grouping shown to contain points of both still water and

sandy deposits. This "overlap" zone is thought to be valid as it trends in the direction of the zone of aqueous deposition. All of the samples in this category are taken to have been formed in exceptionally active lake water conditions. It is essential not to confuse sample points in this category with similarly placed points of boulder clay and fluvioglacial clay (drift) in which the sand is coarse and forms a second mechanical population to the silt and clay "mixture". The fine sandy lake deposits include:

a. Sample No. 12, surface ooze very near to Troutbeck mouth (S14); and Nos. 66, 88, A and B - level gyttja samples from very near Brathay mouth (C1), the C - level gyttja from the same locality is included within the still water group. These samples appear to have been deposited in water which was neither still nor nearly still by the present definition. It is also inferred that Brathay was more active than Troutbeck during A and B - level gyttja deposition but that the position has been reversed at present (or, at any rate, during deposition of surface ooze in April - May, 1961). This may be related to the longer flood plain courses of the main rivers Brathay and Rothay north of the main inlet, with Grasmere, Rydal Water, and Elterwater acting as sediment traps at present, than that of Troutbeck (fig. 4). It may also be due to the more rapid building of a delta shelf at the north end during earlier Post Glacial times and the resulting decrease in water velocity at present when the river enters the deeper water.

b. Samples Nos. 39, 40, 41, near shore silts. These were found in sheltered localities on the western margin of the lake beside the islands (B25, B26, B32), though they were in about one meter depth of water and liable to wave disturbances.

c. Sandy layers which were formed fairly early in the Post

Glacial gyttja sequence, one (No. 137) in the deepest part of the lake opposite Wray Castle (C6), the other two (Nos. 138, 139) in deep water due west of Troutbeck mouth (C13). Also at different levels in the Late Glacial lacustrine sequence, one (No. 174) off Slack Wood Beck (C7), three (Nos. 175, 176, 177) close to the Troutbeck mouth ((C11, C12), and the fifth (No. 178) on the slope up to the "threshold" region (C15). There do not appear to be any particular reasons of locality for these deposits as there are with a and b categories. It is therefore significant that all the four fine sandy lake deposits whose points are in the "overlap" zone are from this category, they all appeared friable and sandy, therefore different from the material around them, but their mode of formation is uncertain.

Other Still Water Late Glacial Material. Some Late Glacial mater-ial which was not known to have been deposited in still water, as opposed to lacustrine sediments, does give its sample points within the group:

a. All but one of those fluvioglacial clays sampled as short cores in the surface sampler from the threshold region, rusty and smooth alike (Nos. 185 to 190 and 202 to 207 respectively from localities S26 to S31, S33, S35, S36, S39). No. 208 from near Lady Holme, further north than the rest, is the exception.

b. Fluvioglacial clay No. 196, sampled at the northern end of the western Lily of the Valley island (B27).

c. The two deltaic clays from Brathay (No.211; B4) and Troutbeck (No. 212; B12) respectively.

It is likely that all these clays were deposited in a dominantly still water environment (glaciolacustrine), though the coarse sand in No. 189 suggests that there was a second mechanical

population in places, which probably comprised material which had been deposited prior to the "ponding" of the lake. These shallow water surface sampled clays as well as No. 196 were thus probably deposited in small temporary lakes (or one lake) on the site of the present threshold. These (this) were neither widespread nor long in existance as indicated by the nearness of localities yield-ing samples whose points are outside the still water grouping (on the islands and S37 near Lady Holme). The points of the deltaic clays within the still water group are in accordance with the postulated ponded lakes at the bases of the two main valleys.

Subdivisions of Still Water Material. The samples within this major group are divided into three subgroups. The first is exclus-ively that of Late Glacial pink lacustrine clays in the "clay third" of the diagram. It is seen that several of these pink clays do not occur within this subgrouping; these exceptions are assumed to be due to erratic laboratory sampling whereby the visual distinction between clay/silt varves and pure pink clay was some-times clearly insufficient for eliminating the possibility of a wrong identification. The Post Glacial lake sediments, Late Glacial dark grey lacustrine silts, and the surface sampled fluvioglacial clays, with the exceptions already mentioned, occupy the rest of the grouping. The second subdivision is based on surface ooze samples only; those collected from Windermere in April - May 1961 (Trip 2) are separated completely from those collected in January 1961 (Trip 1) and those in August 1962 (Trip 5, after heavy floods)and also those from Grasmere, Rydal Water, and Elter-water in August 1962 before heavy floods. The latter three categories occur in the "silt third"of the diagram, the former category occurs partly in the "silt third" and partly in the "clay

third". It is estimated that the Windermere basin environments corresponding to this still water grouping have produced material of median content 10% sand, 55% silt, and 35% clay; variations are the record of fluctuating environments.

Major Glacial Drift Grouping.

The samples outside the still water grouping include most of the fine sandy lake deposits (which are simple deposits); these are thus largely inside, but should be distinguished from, the glacial drift grouping. This second major group contains points of samples in the following categories:

a. Fluvioglacial clays and sands (Nos. 191 to 201 and Nos. 209, 210 from localities B8, B16, B20, B21, B22, B27, B28, B29, B37, B39, B40, and B10, B37 respectively) other than those surface sampled as short cores from the threshold (N.B. No. 208 is outside the still water grouping and No. 196 inside, see above), which are in the still water grouping.

b. Deltaic silts. The Brathay deltaic silts (Nos. 213 to 215) are finer and thus close to the still water group whereas the equivalent Troutbeck samples (Nos. 216, 217) are coarser and well outside it. This relationship is also found in the deltaic clays suggesting that Troutbeck was the more active river at that time.

c. Boulder clays (Nos. 218 to 223).

The most striking feature of the glacial drift grouping (fig. 62c) is that the points are concentrated along the silt - sand edge of the diagram and that altogether they appear to follow the silt + sand third which "wedges into" the silt apex alongside the still water grouping. The general implication may be that the original glacial drift including randomly grouped boulder clay and some less random fluvioglacial deposits, parent

material for the Windermere basin, has largely been washed clean of its original finer silt and clay content by "post drift" aqueous erosion. The fine material was transported and deposited in the nearby still water environments, noteably the main lake Windermere, leaving the remainder of the drift in its original place of deposition. It may be significant that this drift group--ing can be divided into three subgroups. This suggests either that parts of the original drift were formed from the parent boulder clay through redistribution by meltwater into several (three here) well defined environments of deposition, and that the distinctions between the respective eroded end products are still marked; or that "post drift" erosion takes several (three here) well defined forms tending towards 100% sand and pebbles (beach material for example). The appearance of boulder clay sample points in all three groups would seem to support the latter possibility until it is recalled that meltwater on, in, and under the ice may have washed finer material out of an unsorted boulder clay (the definition here) during or even before its deposition by the ice (Wright, 1937, p.27).

Apart from the boulder clay and fluvioglacial sands, several of these drift clay samples contained coarse sand "admix--tures" indicative of two phase deposition (Nos. 191, 192, 194, 195, 197, 198, 200, 208, 216). This suggests that, in many cases, the faster moving meltwater depositing coarse material preceded more sluggish conditions in which the fine "admixtures" were intro--duced to the same sediments causing bimodality. This supports Charlesworth (1957, p.437)who claims that this was the more common sequence of events in the Late Quaternary. It should also be pointed out, however, that the two deltaic sequences at Brathay

and Troutbeck as well as the semi consolidated rusty sand/clay sequence near Cockshott Point (locality no. B37) both showed the reverse trend, probably because the earlier material was formed in special ponded conditions.

Section Showing Environments of Deposition.

The environments in and around Windermere since the ice started to retreat are summarised comprehensively on figure 63. This method of classifying sedimentary environments is similar to that used by Kofoed and Gorsline (1963) who also plotted a triangular scatter diagram and used the groupings to draw a map of present day environments in Appalachicola Bay, Florida. In this study a section is drawn because the whole of the Late Quaternary is being examined, not just the present day.

Figure 63 is to be found folded in at the back of this volume.

Chapter 18. Scatter Diagrams and Statistical Tests.

One-dimensional or Linear Scatter diagrams.

These were simply distribution diagrams and were used both for providing complete sets of properties which are taken as representative of each facies, as well as for testing significant departures from equality of any one facies or group of facies from a second.

Representative Data.

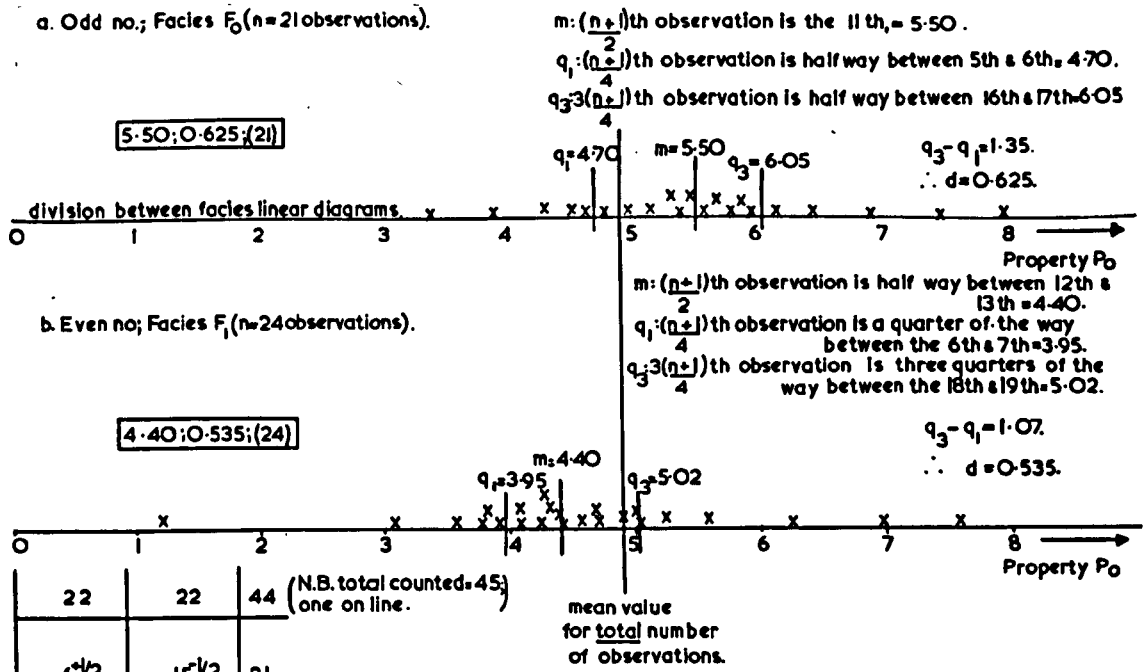
The data from each individual sample in each facies were plotted on linear diagrams, one for each property of each facies (hypothetical examples in fig. 64 a, b). The following values were determined:

a. The number of observations of individual samples in the group or facies (n).

b. The median or mean value (m) which was equal to the $\frac{1}{2}(n + 1)$th observation. "Measure of location" (David, 1953, p.25).

c. The semi interquartile range (d) which was half the difference between the third quartile (equal to the $3/4(n + 1)$th observation) and the first quartile (equal to the $\frac{1}{4}(n + 1)$th observation. "Measure of dispersion" (David, 1953, p.34).

Thus in each cell of the tables (see below, Part III) representative values are listed in the form: m; d; (n). This method applies however many observations are equal to any one of the three quartiles. It is emphasised here that sampling of the different facies may not have been entirely random in each case and that there may be an insufficient number of samples of each. The listed representative properties were probably not, therefore, obtained from perfect population samples and may not be strictly accurate.



22	22	44 (N.B. total counted = 45; one on line.)
$6^{+1/2}$ $10\frac{1}{2}$ -4	$15^{-1/2}$ $10\frac{1}{2}$ 4	21
$16^{-1/2}$ $11\frac{1}{2}$ 5	$7^{+1/2}$ $11\frac{1}{2}$ -5	23

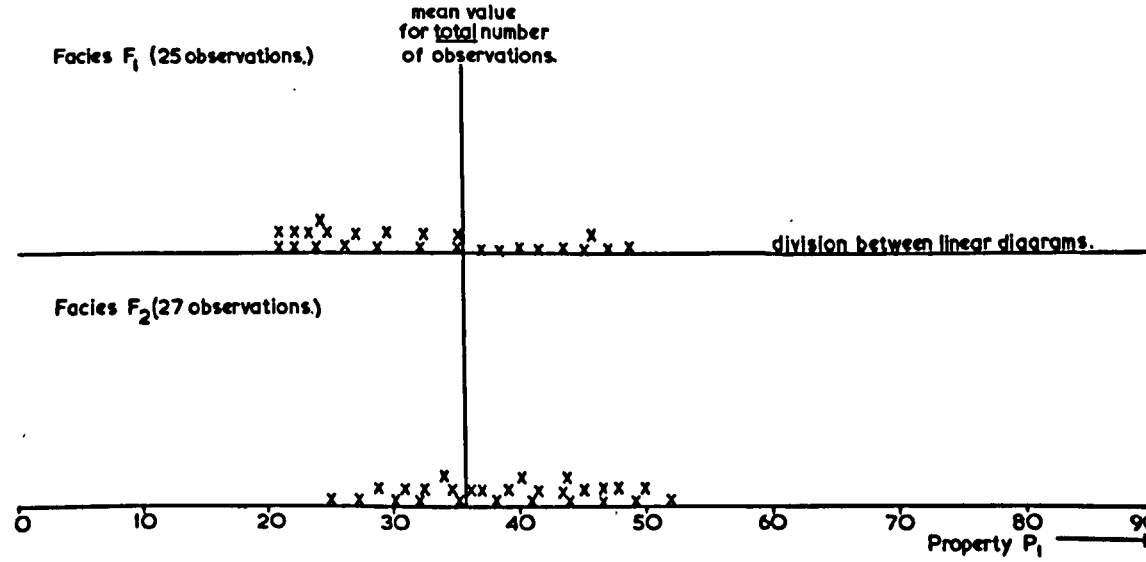
mean value for total number of observations.

$$X^2 = \frac{(-4)^2}{10\frac{1}{2}} + \frac{4^2}{10\frac{1}{2}} + \frac{5^2}{11\frac{1}{2}} + \frac{(-5)^2}{11\frac{1}{2}} = 5.82$$

$P < 0.025$; significant inequality.

Chi-square test; see next section.

c. Chi Square Test for Inequality.



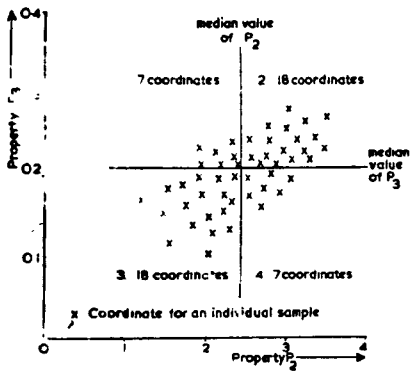
26	26	52 (N.B. total counted = 52)
$16^{-1/2}$ $12\frac{1}{2}$ 3	$9^{+1/2}$ $12\frac{1}{2}$ -3	25
$10^{+1/2}$ $13\frac{1}{2}$ -3	$17^{-1/2}$ $13\frac{1}{2}$ 3	27

$$X^2 = \frac{3^2}{13\frac{1}{2}} + \frac{3^2}{13\frac{1}{2}} + \frac{3^2}{13\frac{1}{2}} + \frac{3^2}{13\frac{1}{2}} = 2.77$$

$P < 0.10$; not significant inequality.

Chi-square test; see next section.

Figure 64. Illustrations for Statistical Methods.



2x2 Table

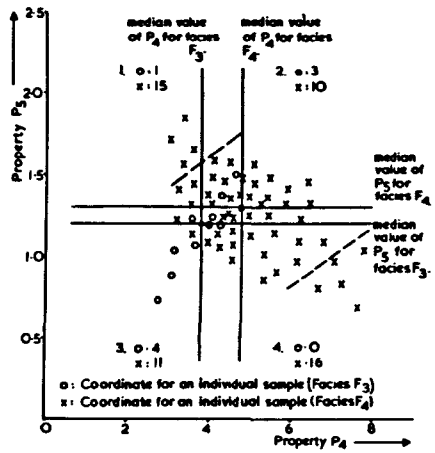
N.B. There is no necessity for this symmetry.

		SUM
25	25	50
1. $O=7^{+1/2}$, $E=\frac{25}{50}$ of 25. $12\frac{1}{2}$, $\delta=-5$	2. $O=18^{-1/2}$, $E=\frac{25}{50}$ of 25. $12\frac{1}{2}$, $\delta=5$	25
3. $O=18^{-1/2}$, $E=\frac{25}{50}$ of 25. $12\frac{1}{2}$, $\delta=5$	4. $O=7^{+1/2}$, $E=\frac{25}{50}$ of 25. $12\frac{1}{2}$, $\delta=-5$	25
SUM		

$X^2=\frac{(-5)^2}{12\frac{1}{2}}+\frac{(-5)^2}{12\frac{1}{2}}+\frac{5^2}{12\frac{1}{2}}+\frac{5^2}{12\frac{1}{2}}=8.0$, $P=0.005$ approx.

Thus the scatter of these data shows a significant trend in which P_2 values increase with P_3 values.

d. Chi Square Test for a Trend.



2 x 2 Tables

a Facies F_3 (o)

	5	3	8
E in quadrants 1 and 3 is $\frac{4}{8}$ of 5.	$1^{+1/2}$ $2\frac{1}{2}$ -1	$3^{-1/2}$ $1\frac{1}{2}$ 1	4
E in quadrants 2 and 4 is $\frac{4}{8}$ of 3.	$4^{-1/2}$ $2\frac{1}{2}$ 1	$0^{+1/2}$ $1\frac{1}{2}$ -1	4

$X^2=\frac{(-1)^2}{2\frac{1}{2}}+\frac{(-1)^2}{1\frac{1}{2}}+\frac{1^2}{2\frac{1}{2}}+\frac{1^2}{1\frac{1}{2}}=2.13$, $P=0.15$ approx

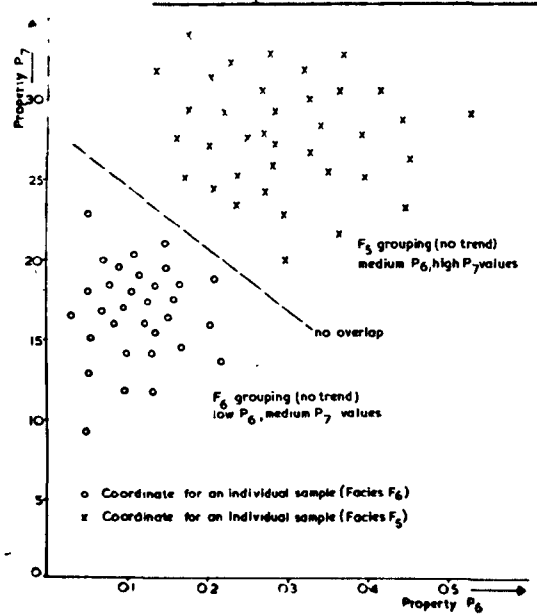
b Facies F_4 (x)

	26	26	52
$E=\frac{25}{52}$ of 26	$15^{-1/2}$ 12.5 2	$10^{+1/2}$ 12.5 -2	25
$E=\frac{27}{52}$ of 26	$11^{+1/2}$ 13.5 -2	$16^{-1/2}$ 13.5 2	27

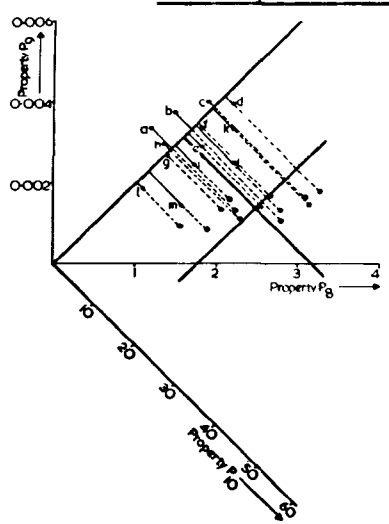
$X^2=\frac{(-2)^2}{12.5}+\frac{(-2)^2}{13.5}+\frac{2^2}{12.5}+\frac{2^2}{13.5}=1.23$, $P=0.25$ approx

Neither scatter shows a significant trend

e. Chi Square Test for Trends.



f. Two Dimensional Groupings.



2X2 Table of the three dimensional distribution

6	6	12
$O^{-1/2}$ 3 $-2\frac{1}{2}$	$6^{+1/2}$ 3 $2\frac{1}{2}$	6
$6^{-1/2}$ 3 $2\frac{1}{2}$	$O^{+1/2}$ 3 $-2\frac{1}{2}$	6

$X^2=\frac{6\frac{1}{2}}{3}+\frac{6\frac{1}{2}}{3}+\frac{6\frac{1}{2}}{3}+\frac{6\frac{1}{2}}{3}>>8$

$P>>0.005$.

This trend is therefore significant; cp. Two dimensional scatter diagram, Properties P_8 and P_9.

•(1) Coordinate for a numbered individual sample (facies F_5 only) on two dimensional diagonals.

• Coordinate for an individual sample (F_5) on three dimensional diagram.

g. Projected "Three Dimensional" Diagram.

Figure 64 continued.

A Test for Departure from Equality of Two Groups of Observations. (Chi-square test explained in David's Chapter 24)

Two linear scatter diagrams were drawn as shown in figure 64 a and b of the same property of two different facies. It was sometimes desirable to know whether these two were the same or different applying a statistical criterion. It was originally hoped to be able to use the $n^{\frac{1}{2}}$ criterion which is simple, but for such tests it is necessary to have a fixed "well known" mean value of the property for purposes of comparison, but rarely here was one of these available. Instead the chi-square test was applied as shown in figure 64c (and also for comparison of the linear groups in fig. 64 a and b) by turning the comparison diagram, in effect, into a two-dimensional scatter diagram and by taking the median value for the total number of observations as the vertical, and the division between the linear scatter groups as the horizontal, quadrant lines which the 2 x 2 tables are built up from. The calculations for the probability of equality of the two hypothetical groups are shown on figure 64c but they are more appropriately explained in the following section on two-dimensional scatter diagrams.

Two-dimensional Scatter Diagrams.

The observations for one property of a group of samples were plotted against those for a second property of the same group. These two-dimensional scatter diagrams were used both for examining the significance of the relationship between the two properties as well as for determining, by visual inspection, groupings of sample points. Previous work in this latter respect by other authors is summarised more appropriately

in Part III.

The Chi-square Probability Test with One Degree of Freedom.

This test was used to discover whether apparent inequal--ities between one-dimensional scatter groups of data (previous section),or apparent relationships between properties (two-dimensional scatter) were significant or not by the 5% probability criterion as shown in the hypothetical case shown in figure 64d.

After all the points, each representing a sample coordinate , were plotted median lines for both the properties (P2 and P3) were drawn independantly of each other as if on linear diagrams (fig. 64 a,b); one horizontal and the other vertical resulting in four quadrants being superimposed on the scatter diagram from which the 2 x 2 table is built up. This 2 x 2 table is equivalent to that drawn in figures 64a and b, and c and it is the pointwhere the chi-square test starts; it is the same for both applications. The numbers of points observed (the observed frequency O) in each quadrant, omitting those equal to either median and thus lying on the lines, were counted and recorded in the centre of the appropriate cell of the 2 x 2 table. The numbers of points expected (the expected frequency E) in each quadrant, on the assumption that there was no relationship between the properties, were calculated and written in the bottom left hand corner of the appropriate cell. The value ½ was added to those two observed frequencies which were smaller than their corresponding expected frequencies, and subtracted from those two which were greater. This process made the four observed frequencies more appropriate for the next stage of the calculation and is related to the view that, for instance in figure 64d, there were not more than 7½ points in the top left hand and bottom right hand

quadrants, and not less than 17½ points in the top right and bottom left. Now O - E (called d) for each cell is written in the bottom right hand corner of the appropriate cell and $X^2 = (d^2/E)_1 + (d^2/E)_2 + (d^2/E)_3 + (d^2/E)_4$.

X^2 was calculated and probability P was determined from Owen's Standard Statistical Tables (1962), section 3.1, pp. 50,51 with f, the number of degrees of freedom, equal to one. The critical value of P chosen for this work was 0.05 corresponding to a X^2 of 3.841. X^2 values larger than this gave values of P lower than 0.05 and vice versa. The value of 0.05, equivalent to a probability of 5%, indicates that there were 5 chances in 100 that the two properties, in reality unrelated, should produce an apparent association (relationship) of sample coordinates of the observed magnitude. The probability that the corresponding number of raisins thrown at the paper should produce an equivalent scatter, this was the criterion for significance. X^2 above 3.841 with P therefore less than 0.05 was regarded as exhibiting a significant relationship; a smaller X^2 was insufficient evidence by this definition.

In figure 64d $X^2 = 8.0$ and $P = 0.005$ approximately, equivalent to a probability of 0.5%, therefore the apparent relationship whereby P2 values increased with P3 values was taken as significant. The hypothetical examples shown in figure 64c appeared to show that P4 values increased with P5 values for samples in facies F3 but decreased with P5 values for samples in facies F4. However, examination of each trend by the chi-square method did not support either of them, as shown in the 2 x 2 tables and subsequent calculations of X^2 and P. Closer visual examination of the scatter groups showed that the apparent relationship

between P4 and P5 for samples in facies F4 was observed only because of those few sample points at the extremities of quadrants 1 and 4 (outside the dashed lines on the diagram). The points inside these lines showed no clear visual trend and those outside were not in sufficient quantity to give statistical confirmation of the apparent trend. The apparent relationship between P4 and P5 for samples in facies F3 was not given statistical confirmation probably only because of the small quantity of data in this respect; it appeared that further sample points would have provided the necessary quantity.

Grouping of Sample Points.

In cases where there were no significant trends on the two-dimensional scatter diagrams, it may have been possible to distinguish and to study groupings of sample points with respect to aspects of sedimentation. Figure 64f shows an extreme hypo--thetical example of the graphical grouping of sample points from two different facies. This type of grouping is presented graphic--ally without statistical tests.

"Three-dimensional" Scatter Diagrams.

There were two methods for plotting observations of three properties of the same group of samples against one another.

a. Equilateral Triangular Diagram.

This method has been widely used in geology; for instance by Kofoed and Gorsline (1963) who plotted sand against silt against clay, and by Strøm (1935) who plotted various chemical contents and based his classifications of the sediments and even of the lakes under examination on the groupings of sample points.

The three properties were always inherently interrelated

numerically by being concerned with three exactly defined categories of total content and thus adding up to 100 percent or its equival--ent for each sample point. The three axes had their 100 percentiles at the three apices of the equilateral triangle respectively and their 0 percentiles at the bisections of the corresponding opposite sides. Thus the three apices were termed by the three end members of the properties concerned. The only case where this method was used in this work was that in which the end members were 100% sand grade, 100% silt grade, and 100% clay grade. This has already been considered in Chapter 17 (fig. 62). The apices were termed "sand","silt", and "clay" respectively and in this case it was found useful to subdivide the area of the diagram into the corresponding "thirds".

b. Projected Three-dimensional Diagrams.

The three properties were not inherently related and did not add up to 100% or its equivalent. These were used in cases (hypothetical example in fig. 64g) where two properties P8, P9 appeared to be related and it was required to ascertain whether a third property P10 tended to follow P8 and P9 jointly. The observations for P8 and P9 were plotted onto a normal two-dimens--ional diagram, the only modification being that the points were numbered (with the sample nos.). A third axis (in two dimensions) was constructed at an appropriate angle through the origin and the numbered points were projected vertically onto it to make a linear resultant scatter group which summarised P8 and P9 as if they were one property only. A fourth axis representing the scale of P10 was constructed perpendicularly to the third axis and the numbered points on this third axis were raised into the ultimate

diagram by an amount equal to their P10 values. The final scatter was examined by the chi-square test or for groupings of points.

Other Tests.

The chi-square test can be used with a number of degrees of freedom (more than one) but this is not done here. Eisenhart (1935) used the method for testing the homogeneity of samples in a series of facies with respect to several different attributes; this was found to be particularly useful for rocks where the facies may not be visually discernible and where the attributes are concerned with aspects of the content of the material. The paper also contains a useful description of the chi-square method.

In this work further simple statistical tests are devised where appropriate at a later stage.

Chapter 19. Graphical Presentation of Data.

The sedimentological properties of material in the Windermere basin have varied in two fundamentally different ways:

a. Geographically, at different localities at the same time.

b. Stratigraphically, at successively later stages at the same locality.

These variations were often best studied graphically as either property variation maps or core property diagrams; and a combination of both variations were plotted onto cross sectional or block property diagrams. The statistical methods were used either for more general work on Windermere results, by providing the representative data and significant differences between them, or for work with wider applications than the present material and of a more general sedimentological nature by providing relationships between properties. The graphical methods were used for more detailed sedimentological work on Windermere itself.

Property Variation Maps.

Techniques used by previous authors.

Reid (1963) has drawn simple contour (isopleth) maps of silt grade % and sand grade % showing sediment relationships with shoreline and bottom topography in Burt Lake, Michigan. Wilson and Opdyke (1941) have studied the distribution of chemical constituents in Tippecanoe Lake south of Lake Michigan in Indiana, showing contoured distribution diagrams for carbonates, silica, and organic matter. Holmes and Evans (1963) have drawn contour maps of mean grain size of non carbonates, carbonate content, and organic carbon in and near Greater Gullivan Bay, Florida; they have related these distributions with postulated tidal and current directions in the bay, on a contoured map.

Kofoed and Gorsline (1963) presented much of their finished material graphically on property variation maps. They related contoured distribution diagrams of mean grain size (≡ median diameter here), standard deviation (≡ sorting), carbonate content, and carbon content to physiographic distribution maps showing submarine topography, sedimentary environments, and sediment types. The same authors proceeded to obtain approximate "regional trends" for the properties concerned by considering an imaginary "plane dipping surface" for each (loc. cit., figs. 6, 11, pp. 213,217). The more accurate "residual maps", which were the resultants after comparing the contour maps with the appropriate regional trends, were studied with respect to the geological significance of local variations. After completing this study of Windermere sediments the present author suggests that further justification is required before even the practical validity of this method can be certain. There are apparent "regional trends" in both Late Glacial and Post Glacial sediments in the North Basin of Windermere (Part III) from the Brathay mouth, or main inlet at the northern end, southwards to the threshold region in which the grain size, organic content, and flocculation decrease away from the main inlet and sorting improves. It is possible that a series of plane dipping surfaces could be postulated for these trends and residual local variations examined more accurately such as the coarseness, high organic content, and high flocculation near Troutbeck mouth; and the apparent slumping and subsequent coarseness in the early Post Glacial material at C8 (this latter phenomenon is considered in greater detail in later sections). There are, however, two potential sources of objection to this method with respect to Windermere:

a. The regional trends are not plane dipping surfaces. Their exact forms are impossible to assessaccurately which would appear to be essential for a close study of residual local variations.

b. There does not appear to be a simple fundamental distinc-tion between the regional north south trend "starting"at the main inlet, and the residual trend "starting" at Troutbeck mouth which is again approximately north south.

Both these objections point to the theoretical considerat-ion that regional trends are, in fact, wholly artificial and are composed of an infinite number of residual local variations; and that the two cannot be distinguished fundamentally. However, since the method has been applied successfully in Appalachicola Bay it clearly has its practical advantages. It was not, however, used in this study of Windermere for the two reasons mentioned above.

Van Andel and Posthma (1954), working on the recent sediments in the Gulf of Paria off the Orinoco Delta between Venezuela and Trinidad, used several different kinds of property variation maps to show their results graphically to the best advantage: contoured maps, shaded maps, filled dot maps with varying sized dots, and segmented dot maps with the filled segments varying. This study was largely concerned with present day sedim-ents and sedimentary environments as they affected the micro-faunal remains. It was a comprehensive study on a large scale so that the results are highly detailed in spite of the large area under investigation. The present work on Windermere lake is concerned with a more "homogeneous" areathan the Gulf of Paria; there are also comparatively fewer data, with the result that the methods used in the excellent work of Van Andel and Posthma are

not generally reproduced here.

Present Work.

Ideally a property variation map would represent the Windermere basin as it was at one moment in the Late Quaternary history of the area. Sediment property variations would be plotted and examined to discover features of sedimentary significance at that moment with respect to erosion, transport, and deposition of sediment particles. In fact, the uncertainties of chronological correlation of "contemporary" samples in one "facies" increase progressively in the older sediments:

a. Surface ooze. All samples in any one "facies" were collected within a few days of each other; likewise with other present day deposits.

b. Gyttja. Correlation depended upon two assumptions (see Chapter 4): i. That the two rates of deposition at any locality have been uniform throughout the two phases of Post Glacial history represented first by the transitional sequence and then by the gyttja itself. This assumption is not accurate at every locality; an extreme hypothetical case is shown in figure 16 and the cores actually sampled are illustrated in Appendix No. 2 (fig. ii).

ii. That there has been no form of discontinuity such as slumping or erosion in the deeper water from which the cores here were taken, as occured in the shallower water during the Post Glacial period (Pennington, 1947a). The core sampled at locality C8 (core no. 11, fig. ii) showed evidence for slumping in the presence of the six inch thick pink clay band in the transitional sequence near the top of the Late Glacial clays. The same core also showed evidence for an active period of water movement at that point just after the slumping in the increase of grain size (Part III, table 29b)

above the clay band. This is the only core sampled in this study to give clear evidence contrary to the latter assumption and it may be an isolated case due to its nearness to the shoreline at High Wray Bay.

c. Late Glacial Material. A general scheme of correlation was not attempted due to the slumping in many cores (lacustrine material) and to the uncertainty of the sequence of events outside the main lake. For general purposes it was found necessary to assume that the boulder clay samples, the deltaic clay and silt samples, and the surface sampled fluvioglacial samples were respectively contemporaneous, though property variation maps were not drawn making this assumption.

As a result, first of these uncertainties and second of the number of different properties and different "contemporaneous facies" each requiring an individual property variation map, these are not presented with this thesis though many have been plotted and studied. Instead, geographical variations within the different lake "facies" only, both Late Glacial and Post Glacial, were studied in four arbitrarily chosen zones (fig. 19 a,b):

A. Off Brathay mouth.

B. South of Brathay region (C8 not included, see above).

C. Off Troutbeck mouth.

D. South of Troutbeck region.

Thus geographical property variations were examined statistically within these regions and the results plotted on the more general property maps shown in Part III. Late Glacial material outside the main lake was used for more general conclusions only and not plotted on maps.

N.B. Locality nos., sample nos., and sample properties may be cross checked onto figure 19 using tables i and iii.

Core Property Diagrams.

Techniques Used by Previous Authors and at Present.

Van Andel and Posthma (1954, fig. 46, p.98) showed pH and Eh variations down certain sediment cores from the Gulf of Paria by plotting a vertical depth scale against a horizontal property scale and joining the resulting sample points with straight lines, thus obtaining a visual representation. Meade (1963, table 1, p.289) tabulated sample data down one core from the San Joaquin Valley of California and thus obtained a less bulky presentation of data which none-the-less required a more careful examination than the purely visual method. Hough (1955) used the sedimentary evidence of a number of core samples to postulate a comparatively recent (4000 years ago, assuming steady deposition) low level stage in Lake Michigan when the water level was 350 feet below that at present. The conclusion was supported by fossil evidence in the coarser layer concerned and by geomorphological evidence around Lake Michigan and the neighbouring Lake Huron.

The visual method used by Van Andel and Posthma was used in this study at first, but the original core diagrams were too bulky to present with this thesis because of the large number of properties under examination in the fifteen cores and also because much of some of the horizontal property scales were wasted merely for one or two exceptional data. Instead stratigraphic variations at different localities in the lake were tabulated comprehensively and examined statistically in Part III.

In certain cases other than the long cores, properties of different facies sampled at one locality were tabulated with each other for comparison. For example:

a. Ooze/A - level gyttja in the surface sampler short cores, all properties.

b. Rusty/smooth fluvioglacial clays in the surface sample short cores, all properties.

c. Deltaic silt/clay shoreline samples, all properties.

d. Beach material/drift shoreline samples, roundness analyses and grain size distribution of the coarse fraction.

Generalised results as well as those from localities of particular interest are discussed in Part III.

Representative Particle Size Curves.

Specific sample curves are not generally presented graphically. Instead representative cumulative curves are calculated from the representative data and plotted as follows:

The statistical data are known, Md, So, Sk, and k, Md is known in both mm and ϕ units, Sk is equal to $(Q1Q3/Md^2)$mm.

Thus $Sk \times Mdmm^2 = Q3Q1$ .....(1).

So is equal to $(Q3/Q1)^{\frac{1}{2}}$ mm.

Thus $So^2 = Q3/Q1$.....(2); multiply (1) and (2).

Therefore $(Sk \times Mdmm^2 \times So^2)^{\frac{1}{2}} = Q3mm$; from (2):

$(Sk \times Mdmm^2 \times So^2)^{\frac{1}{2}}/So^2 = Q1mm$.

Thus Q1ϕ and Q3ϕ are both determined.

k is equal to $(Q1 - Q3/2P90 - 2P10)\phi$, $P10 - P90 = (Q1 - Q3)/2k$.

It is assumed that the curve tails off after the quartiles equally at the coarse and fine ends, and, for convenience,

$(P10 - P90)\phi - (Q1 - Q3)\phi = 2t\phi$.

The value tϕ is added to Q1ϕ and subtracted from Q3ϕ to give approximations for P10ϕ and P90ϕ respectively.

Thus the phi values for P10, Q1, Md, Q3, and P90 are known and the representative curve is plotted. Bimodal curves require to be adjusted according to the sand grade percent (ϕ4). It is also necessary to check the curves with the clay percent (ϕ9).

PART III. SEDIMENTOLOGICAL IMPLICATIONS OF PHYSICAL AND MISCELLANEOUS RESULTS.

Chapter 20. Introductory Discussions on Mechanical Analyses and their Interpretations with special reference to analyses of Flocculating Windermere Sediments.

Theoretical Discussion Based on Spencer's Hypotheses (1963).

Any sedimentary study of mechanical distrib--utions is confronted by the problem of interpreting those distributions in terms of transport, depositional, and post depositional environments of the particles. Spencer's work is outlined at some length here because it is the most recent discussion on particle size populations with special reference to their occurence in clastic sediments and because it incorporates previous discussions and views on the same topic. It is useful in this respect, particularly because it analyses theoretically these problems of interpretation using standard statistical techniques for the graphical dissection of heterogeneous distributions.

Spencer's Log Normal Populations and Sediment Categories.

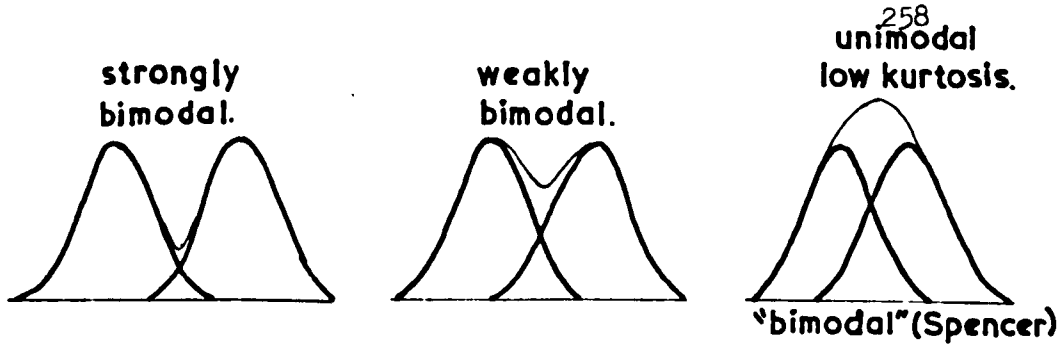
Spencer has discussed the statistical interpretation of grain size distributions of clastic sediments with respect to phases of deposition and concluded that there are three fundamental log normal sediment particle populations in nature: gravel, sand, and clay; with deficiencies between them. Pettijohn (1957, Chapter 2) has also recognised these natural deficiencies and specifically placed them at 2.0 to 4.0 mm

and $\frac{1}{8}$ to 1/16 mm respectively. Spencer claims that most natural deposits are in one of three categories of particle size distribution.

a. One of the three fundamental log normal populations existing alone. Spencer says that sediments in this category are the only truly unimodal sediments and that measurement of true "dispersion" (sorting, Chapter 13 of this thesis) can only be made of one of these.

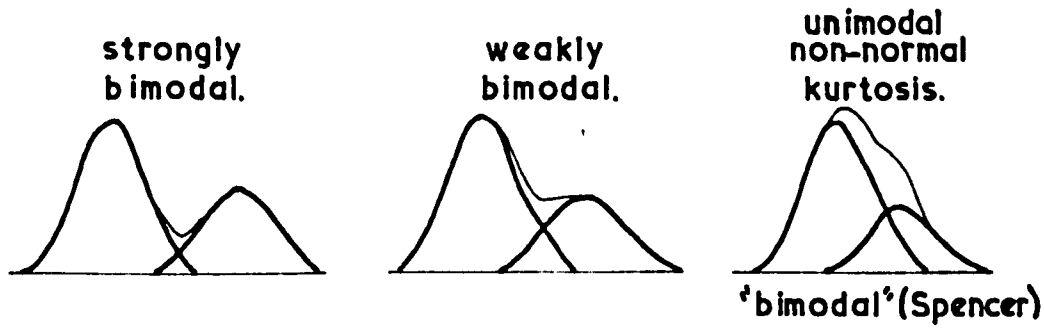
b. "Mixtures" of two or three of the populations in any proportions. Spencer says, in support of Folk and Ward (1957), that these sediments may give apparently unimodal frequency curves, when the particle populations and the "mixing" processes were appropriate, but that they are truly bimodal mixtures. This concept is illustrated here in figure 65 a and b (reproduced from Spencer's figures 1 and 2). These figures show hypothetically the processes of mixing two log normal distributions where the difference between the medians, the respective standard deviations, and proportions of material vary independently to give strongly bimodal and weakly bimodal frequency curves; as well as combined unimodal curves showing either the log normal form (fig. 65a) or assymmetry and non normal kurtosis (fig. 65b).

c. Truncated forms of the log normal populations (a), or of the "mixtures" of these (b), or "mixtures" of the truncated forms. Spencer says that collections of sediment particles (in either of the categories a or b), whether in suspension or deposited, may be subjected to "perfect" or "less efficient" sorting processes whereby a "split" is made and the original distribution truncated. If the sorting processes



a. Mixtures of similarly disposed log normal distributions, difference between medians varies.

(reproduced from Spencer, 1963)



b. Mixtures of dissimilar log normal distributions, difference between medians varies.

(reproduced from Spencer, 1963)

c. Sediment Types. (after Krumbein and Aberdeen, 1937)

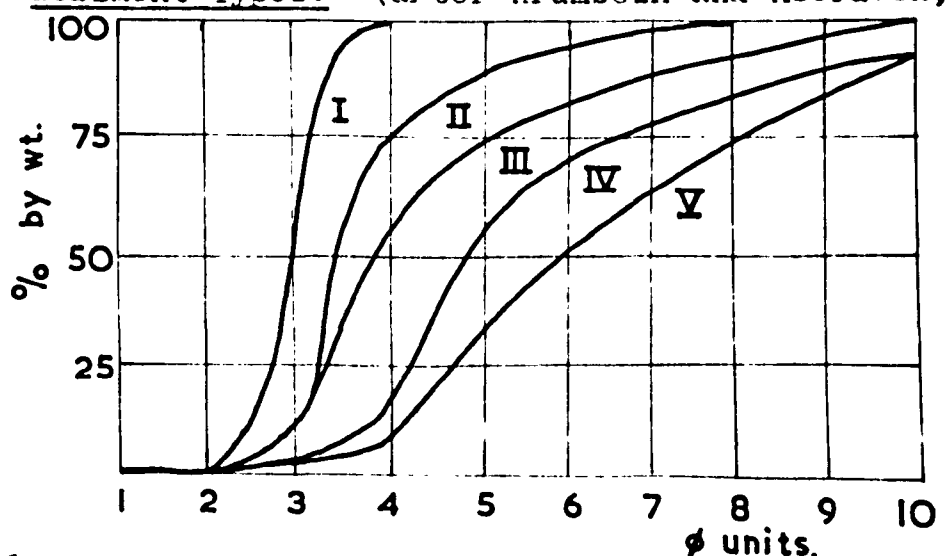


Figure 65. Curves to Illustrate Spencer's Hypothesis.

are perfect the split occurs at a single size grade, with no overlap, so that the deposited material is entirely larger than that size, and the material swept away is entirely smaller. If the sorting processes are less efficient there is a variable zone where the lower size grades of the deposited material overlaps the upper size grades of the material swept away. This truncation effect is not illustrated here but figs. 6 to 10 (loc.cit.) show it hypothetically. This split of sediment particle distributions by the sorting processes results in two truncated distributions which may themselves be mixed together or with other distributions at a later stage.

Spencer claims that most natural deposits are in one of these three categories and discusses results from sediments in the Mississippi delta, 98 by Krumbein and Aberdeen (1937) from Barataria Bay and 260 by himself, to demonstrate the validity of this conclusion. Of particular interest is Spencer's analytical study of Krumbein and Aberdeen's figure illustrating their classification of Barataria Bay material into five sediment types on a basis of particle size distribution (reproduced here as fig. 65c). Spencer simplifies this classification by claiming that types I and V are log normal and are equivalent to the fundamental populations of "sand" and "clay" respectively. Types II, III, and IV are skewed because they are "mixtures" of the log normal sand population and the log normal clay population; these mixtures are in different proportions which results in the three intermediate types defined by Krumbein and Aberdeen. Both publications recognise truncation of these type distributions and mixtures

of the truncated forms.

Suggested Limitations to Spencer's Hypothesis.

For the purposes of this study of Windermere material the present author suggests that there is likely to be some confusion as a result of Spencer's failing to distinguish clearly between his strictly hypothetical statistical analyses of particle size frequency curves and his applica-tions of these to natural sediments. A theoretical distinction between "mixtures" and mechanically bimodal sedi-ments is made here in an attempt to eliminate this confusion. Friedman (1962) reiterates Udden's "log normal law" (1914) by saying that natural deposits tend to have a log normal mechanical distribution (particle size or settling rate) and that departures from this are indicative of sedimentary environment. The present study uses this concept as the premise for the deductions which are to follow; it is more concerned with the mode of formation of a sediment than with the particle size populations of which it is composed (Part III). A unimodal mechanical distribution has already been defined (Chapter 13) as a curve having one mode or maximum only; it indicates more or less simple aqueous deposition (Chapter 17) though it may be composed of one, two, or three of the fundamental particle size populations, "unmixed", "mixed", or "truncated" (a,b,c categories, see above). The more genetically important environmental factors, however, are determined by studying the statistical properties of the frequency curves (whether it is "mixed" or "unmixed"): the median, the sorting (or "dispersion"), and the departures from

log normality exhibited by skewness and kurtosis. A bimodal mechanical distribution has already been defined Chapter 13) as a curve having two modes or maxima with one minimum or antimode between them. By this standard statis-tical definition there cannot be a bimodal distribution if the two modes are not evident on the frequency, curve a case which Folk and Ward (1957) and Spencer (1963) claim to be possible when two (or more) of the fundamental populations are appropriately mixed (fig. 65a,b); instead a bimodal distrib-ution indicates complex two phase deposition (Chapter 17).

It is, then, being claimed here that Spencer's statistical analysis of mechanical distributions are valid and useful but that his concept of the three fundamental populations and their mixing to form natural sediments, though a useful sedimentological "model", is less genetically important than the premises that simple aqueous sediments are unimodal and that median, sorting, and departures of skewness and kurtosis from log normality are indicative of sedimentary environments. It is also claimed that Spencer's use of the term bimodal may result in some confusion; the standard definition insists that the two modes are evident on the curve and bimodal sediments are thus taken to have a complex sedimentary history.

Natural Flocculation of Fine Grained Bottom Sediments with reference to Post Glacial Windermere Material. (N.B. This discussion is intended to be general, though it applies specifically to the organic flocculating Post Glacial sediments of Windermere).

The occurence of flocculation among the finer grades of material under certain aqueous conditions has not been considered by Spencer and is a further limitation of his work with respect to the interpretations of fine grained mechanical analyses. A second premise is required in this work, namely that the deposition of the bottom sediments in Windermere is a "simple" process so that the natural mechanical settling distributions are unimodal (this is discussed in detail later in this Chapter). However, it has already been mentioned (Chapter 13) that both the dispersed "particle size" distributions (c-analyses) and the flocculated "settling rate" distributions (b-analyses) are markedly bimodal (figs. 47, 48, 54) and the validity of these results has been demonstrated (table 25, fig. 55). It was possible to reconcile these apparent anomalies with the above premise only by making two assumptions;

a. That flocculation just prior to the deposition of the finer material in the second, and generally more important, group gave the entire deposit a unimodal natural mechanical distribution whereby the larger and faster settling flocculos occupied much of the fine part of the settling distribution alongside a small proportion of discrete silt (and clay) sized rock fragments (fig. 66). A small proportion of the flocculos may have settled faster than the finest sand though most of this first, and generally less important, group settled as discrete sand sized particles. Figure 66 shows this assumption hypothetically; it is emphasised, in view of the previous discussions in this chapter, that there is no reason to suppose that the natural settling distributions are log normal,

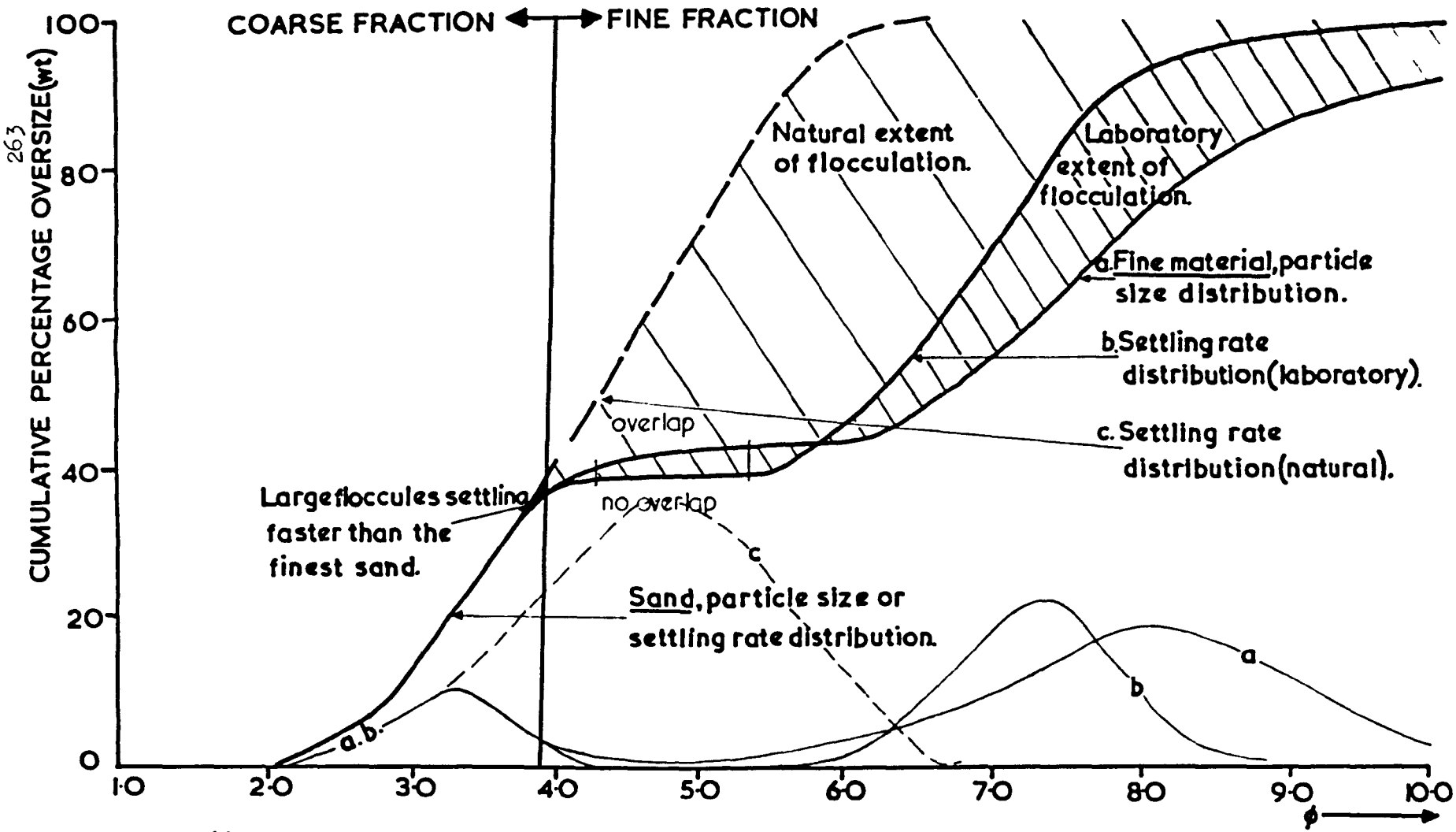


Figure 66. Comparisons between Hypothetical Curves obtained in the Laboratory and a Hypothetical, approximately log normal, Curve which may approximately represent the Mechanical Settling Conditions in the lake. (N.B. True case may not be log normal)

as is the case with this hypothetical illustration.

b. That the natural settling conditions were not reproduced successfully in the laboratory, as was attempted by analysing the flocculated settling rate distributions of lake material using water from Windermere as the settling medium. The flocculated curves, however, were generally less markedly bimodal than the dispersed curves (fig. 66) as expected. Mackereth (personal communication, 1963) suggests that lake sediments are chemically altered by oxidation when removed by the sampling process from their in situ reduced state and mixed, for example, with oxygenated water. The most important chemical change here is the oxidation of ferrous sulphide (FeS) to ferric hydroxide floccules ($Fe(OH)_3$) and sulphuric acid (the presence of this acid decomposition product is supported by the pH results from this study - Chapter 21 and 22). Both these products may have serious effects on the reproducibility of natural settling conditions so experiments were devised here involving the addition of varying quantities of very dilute sodium hydroxide solution to lake water suspensions of Windermere material. There was no appreciable effect, either visible or measurable, in the Sedimentation Balance, until what appeared to be a critical stage was reached at which the material flocculated so intensely that it settled too fast for measurement. Reid (1963) collected recent material from Burt Lake, Michigan, along with considerable excess lake water to minimise post sampling alterations. In this respect, also, it should be said that no attempt was made here to refrigerate the Sedimentation Balance tube to lake temperatures so that whether flocculation varies significantly

or not with the temperature of its environment was not dis-
-covered.

If natural flocculation and unimodal settling cond-
-itions had been reproducible, their results would probably have been of an importance equal to the dispersed particle size results of the corresponding material and the statistical data studied would have been taken from both these frequency curves. Thus a considerably more complete understanding of Windermere deposition would have been obtained. However, this is not the case and, due to the uncertainty and dubious re-
-producibility of the flocculated results, the statistical data from the more reliable particle size frequency curves are used for these sedimentological studies. Measures of maximum flocculation and of the particle size at which it occurs (Chapter 14) are used to denote the degree of floccul-
-ation observed in the laboratory. For the purposes of this work these are taken to be approximately proportional to the true flocculation though their uncertain reliability is re-emphasised.

Inherent Statistical Properties of the Post Glacial Windermere Material as examined in this study, and the resulting limitations of the Statistical Data.

The finest particles in the coarse group in the bimodal distributions are at about $\phi 4.5$ to $\phi 5.0$ (or in the fine fraction); likewise the coarsest particles in the fine group. Sometimes there is evidence for an overlapping of groups (particularly when the fine fraction was dispersed), and sometimes they do not appear to overlap (particularly when the fine fraction was flocculated); figure 66 illustrates

this factor. The purely arbitrary practice adopted here for reasons of practicability, of analysing the two fractions separated at ϕ4.0 instead of the two groups (Chapter 13), introduces inherent statistical biases to the distributions of the two fractions, and thus to the data derived from them (this has already been illustrated in figure 54). This practice causes the coarse group of the bimodal distribution to be studied with its "fine tail" (material between ϕ4.0 and ϕ4.5 to ϕ5.0) removed; and the fine group of the distribution to be studied with its own "coarse tail" (material just smaller than ϕ4.5 to ϕ5.0) increased by the addition of the "fine tail" of the coarse group. The sets of statistical data from the two fractions are thus biased as follows; though only in definitely bimodal material (such as Post Glacial organic deposits). There are no statistical biases in unimodal material (such as shore silts) or in material which occurs exclusively in one or other of the fractions (such as Late Glacial lacustrine clay and silt, and beach deposits):

a. MD (coarse fraction) is inherently slightly coarser than the median of the coarse group.

Md (fine fraction) is inherently slightly coarser than the median of the fine group.

b. SO (coarse fraction) is inherently slightly lower (better sorting) than that of the coarse group.

So (fine fraction) is inherently slightly higher (poorer sorting) than that of the fine group.

c. SK (coarse fraction) is inherently slightly positive (decreased "fine tail" ≡ increased "coarse tail") whereas the coarse group has no inherent skewness.

Sk (fine fraction) is inherently slightly positive (increased "coarse tail") whereas the fine group has no inherent skewness.

d. Kurtosis values are probably biased also, but it is uncertain in both cases.

Further inherent biases were introduced by the use of the dispersed " particle size" curves (c-analyses, without organic matter, see Chapter 15) to calculate statistical data; instead of the flocculated "settling rate" curves of lake material (b-analyses, with organic matter) which it has been assumed was not obtained in the laboratory. If the present assumption is correct and the natural mechanical settling distributions are unimodal, there is only one true set of statistical data representing the settling conditions of each sample of bottom sediment; and no purpose would be served by dividing these combined analyses into the two fractions. The resulting biases in the distributions of the fractions are illustrated in figure 66. It is re-emphasised that the natural curve is not known to be log normal as drawn here; and also that this type of inherent bias is only accounted for in material which is known to flocculate (such as Post-Glacial organic deposits). Late Glacial material is probably more or less unaffected by it:

a. MD and Md; dispersion certainly made Md considerably finer than the true median which, in turn, is probably finer than MD and is probably in the region of ϕ4.0 to ϕ6.0 (0.064 mm. to 0.016 mm.).

b. SO and So; Sherman (1953) first showed the effect whereby flocculation caused natural mechanical distributions

of fine grained material to be comparatively well sorted by "normal processes of deposition" in contrast to the dispersed distributions which are poorly sorted. Thus dispersion would make So a considerably higher value than the true sorting. The relationship between true sorting and SO is not known though it is probably not so low a value as here.

c. SK and Sk; it will be shown (Chapter 22) that the particle size at which the maximum amount of flocculation of Windermere material occurs is generally at the finest end of the scale between $\phi 7.5$ and $< \phi 9.0$ (0.0055 mm and less than 0.002 mm) though the latter cases were not measurable accurately. It was reasonable to expect this because the cohesion of discrete particles to form floccules would normally be considerably less impeded physically by small particles. Sherman (1953) provides further evidence for this higher flocculation of smaller particles by showing that the particle size distribution of grains within an individual floccule is better than that of the entire sample of which it is a part. However, dispersion of the same material would give <u>inherent negative skewness</u> to the particle size distribution due to the large proportion of small particles and particularly non organic colloidal material in some cases (fig. 58), originally strongly flocculated, now giving weight to the fine tail. Thus, though true skewness biases are unknown, Sk has an inherent negative tendancy; the relationship between true skewness and SK is not known.

d. Kurtosis values are probably biased also, but it is uncertain in both cases.

A Summary of these Inherent Biases.

As a result of these two sets of biases to the statistical data, the first set was deduced mathematically and the second by comparing the hypothetical curves on figure 66, their limitations with respect to sedimentological interpretations particularly of Post Glacial lake deposits, have become apparent:

a. It is uncertain how the coarse fraction distribution is affected by flocculation of the fine material; there are also uncertain mathematical biases in all four attributes (MD, SO, SK, K); and the number of observations made on coarse material was strictly limited by its low proportion in many of these lake sediments (Chapter 13). The data were not used, therefore, for studying detailed differences between samples from different localities and stratigraphic horizons. They were useful in a more general sense, however, by providing representative data for obtaining a comprehensive understanding of lake sedimentation and for analysing the coarser material in sediments formed outside the main lake, either Late Glacial or Post Glacial.

b. The fine fraction distribution is more certain in its implications. Dispersion made it, in effect, finer, worse sorted, and negatively skewed. The mathematical biases made it, in effect, coarser, worse sorted, and positively skewed. The median diameter (Md) has two inherent biases working in opposite directions though the mathematical bias is probably negligible compared with that caused by dispersion. Md of Post Glacial lake deposits, therefore, is taken as representative of, though not equal to, the coarseness of the materials'

grain size distribution prior to flocculation and actual deposition and is therefore significant with respect to the preceding aqueous transport phase of lake deposition. The sorting coefficient (So) is inherently biased, by both considerations, to give a higher value (poorer sorting) than the true case, and the mathematical bias is probably insignificant compared with that caused by dispersion. So of Post Glacial lake deposits cannot be taken as representative of the "dispersion" (N.B. statistical sense) of the material's grain size distribution prior to flocculation and actual deposition because flocculation is also selective, by itself, in the process of reorganisation of the particle size grades to be deposited. So is therefore taken more as a measure of flocculation (high So ≡ high flocculation; fig.66: also see Sherman, 1953) than of the true size"dispersion". The relationships between these two properties, however, is complex. The skewness coefficient (Sk) of Post Glacial lake deposits has two inherent biases working in opposite directions. Skewness, however, is a comparatively subtle statistical property and the relative importance of these two biases is uncertain. It will be shown that the grain size distributions of some flocculated fine material have negative skewness and others have positive skewness. There is no evidence to conclude from the relative abundances of these two tendancies which (if either) bias is generally more important, the mathematical positive bias or the negative bias caused by dispersion (Chapter 22). Sk is, therefore, not given detailed consideration here for these Post Glacial lake deposits but the values are used in a more general sense, by providing

representative data, for obtaining a comprehensive understanding of the sedimentation of this material. It is also used to discuss certain processes effective during deposition of some non flocculating sediments. The kurtosis coefficient (k) is a very subtle statistical property and is not given detailed consideration in this study. It is also emphasised that the number of observations made of the kurtosis of fine distributions was strictly limited by the lower limit of application of the Sedimentation Balance (Chapter 13). However, k is used in a more general sense, by providing representative data, for a comprehensive understanding of the sedimentation of fine material.

The one other property of particular importance with regard to the deposition of flocculated material is the sand grade %. It is this which is taken as representative of, though not equal to, the proportion of coarse unflocculated discrete particles to fine flocculated material.

Processes of Deposition of Flocculating Windermere Post Glacial Lake Sediments.

In this respect, it was noted that the two Siltmeters gave no readings at all which indicated that there was a concentration of less than 100 parts per million (solids suspended in liquid) in all parts of the lake, including near the large river mouths, and at all depths down to the sediment/water interface. These experiments were performed in January 1961 (Appendix No. 2) when the weather had been comparatively dry for several weeks. They indicated that the sediment transported into the lake during normal weather

conditions is negligible and that the bulk of it is brought in by the rivers and streams in flood after heavy rains. Thus in Windermere, following Eakin (1936, also see Chapter 2), it is assumed that there are, during floods, "dense turbidity currents of finer material underflowing along the lake floor the less dense desilted water above" and spreading out rapidly from the deltas around the river mouths, at which the coarse sand and pebbles were all deposited. It was observed, however, that the turbid surface water was not desilted immediately off the river mouths but spread out as a fan with fairly well defined margins (see below). Thus it is assumed that the bottom sediments, at present anyway and probably throughout the Post Glacial period (see Chapter 21 for the Late Glacial), have accumulated spasmodically in this manner. The detailed mechanical analyses of surface ooze collected during floods (Trip 5, Appendix No. 2; August 1962), and comparisons with other ooze samples, are discussed in Chapter 22. During these active stormy periods there are two opposing tendancies acting on the finer material involved with these turbulent sediment-laden "turbidity" currents. Namely mechanical dispersal versus electrostatic attraction:

a. Mechanical dispersal through erosion and transport of fine material. These turbidity currents may carry off, disperse in suspension, and redistribute the mechanically vulnerable semi liquid upper layers of previously deposited material. All the particles remain discrete and in suspension and their mechanical distribution is probably unimodal also with respect to particle size but poorly sorted (Kuenen, 1951;

Kuenen and Menard, 1952). Thus the material finally tends to accumulate most thickly in the deepest parts of the lake due to gravity (Eakin, 1936). The coarser discrete particles may start settling as the turbidity currents lose impetus; more full accounts of deposition from these turbulent suspens-ions are given by Kuenen (1951) and Kuenen and Menard (1952).

b. Electrostatic attraction causing flocculation and deposition of fine material. The fine particles flocculate and settle rapidly out of suspension due to their "mass effects" (Eakin, 1936) and to the chemistry of the lake environment. Their mechanical distribution is again probably unimodal though reorganisation (new sorting of size grades, see above) is necessary for the new floccules to settle with the discrete larger particles. This reorganisation causes the particle size distribution to be bimodal.

Thus it is likely that flocculation only occurs immediately before deposition during one particular active phase and that it occurs because the electrostatic tendancy for the particles to flocculate (b) overcomes the mechanical tendancy to maintain them discrete and in suspension (a). Thus it is that the sand/silt/clay triangle (fig. 62; dispers-ed analyses, see Chapter 17) is representative of, though not equal to, the true distributions just prior to deposition.

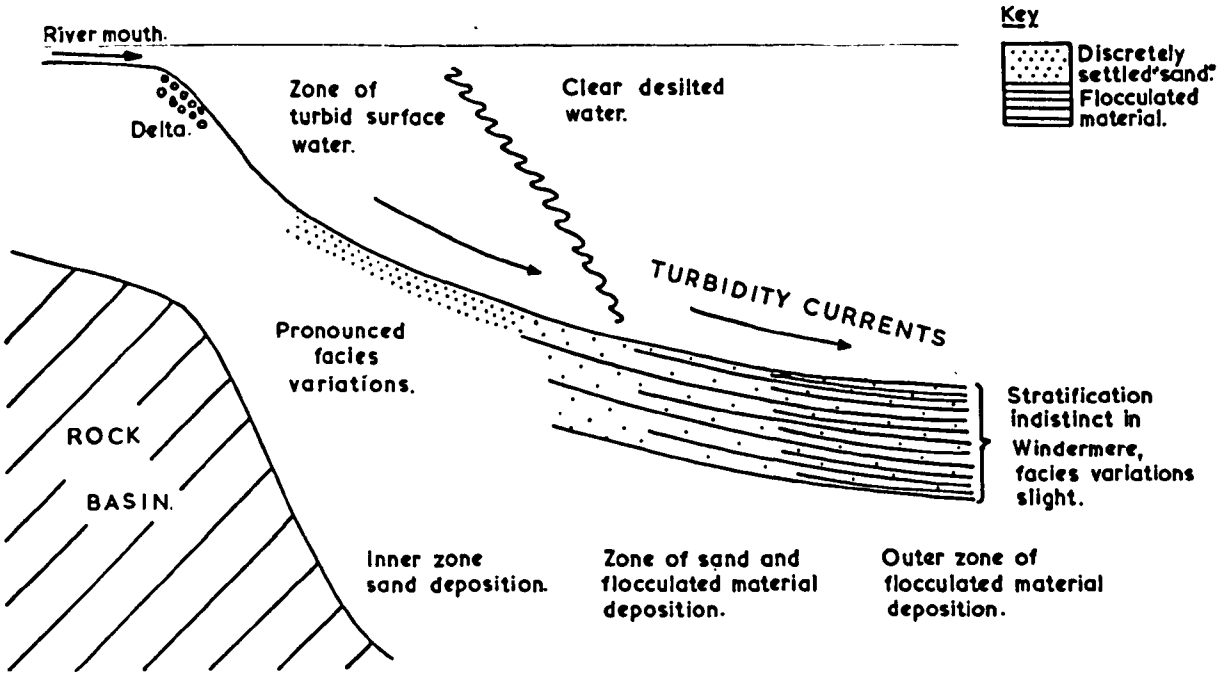
Zones of Deposition - Hypothetical

The coarsest stream load, therefore, is deposited at the delta after which turbidity currents leave the river mouth moving towards deeper water due to gravity. They gener-ally have maximum impetus just after they are formed on enter-ing the lake and, as this is gradually lost, much of the

remaining coarser fraction of the load settles as discrete particles within a comparatively narrow radius from the river mouth (fig. 67; a, section; b, plan). Beyond this sufficient impetus, and hence potential for mechanical dispersal, has been lost for electrostatic flocculation to start and some fine material is thus deposited with the discrete coarser fractions. Further out the proportion of flocculated fine material to the coarser material increases; and in the deeper parts of the lake deposition occurs almost exclusively due to flocculation and not due to discrete mechanical settling. The approximately concentric zones and their margins would be expected to expand and contract with respect to the river mouths according to the strength of the river water currents entering the lake. Thus, as the storm's effects finally wane the zones withdraw to their normal positions near the river.

The effect, on the mechanical distributions of bottom sediments, of the narrow zones of turbid surface water around the river mouths during a storm (fig. 67) is uncertain. It is significant that it is not a wide zone and has fairly well defined margins, similar to the effect when a charged river enters the sea in which the less dense river water spreads out as a "floating fan" (Natland and Kuenen, 1951, p.88). It is likely that there is a tendancy (largely chemical in Windermere) for the material in suspension to flocculate and settle at the edge of the zone, which suddenly overcomes the weak opposing surface water currents, so that it is deposited out of suspension and incorporated into the faster moving turbidity current near the bottom. However, the possibility that this material is ultimately diluted in suspension throughout the body of the lake and that it settles as a second phase (bimodal

a. Section.



b. Plan.

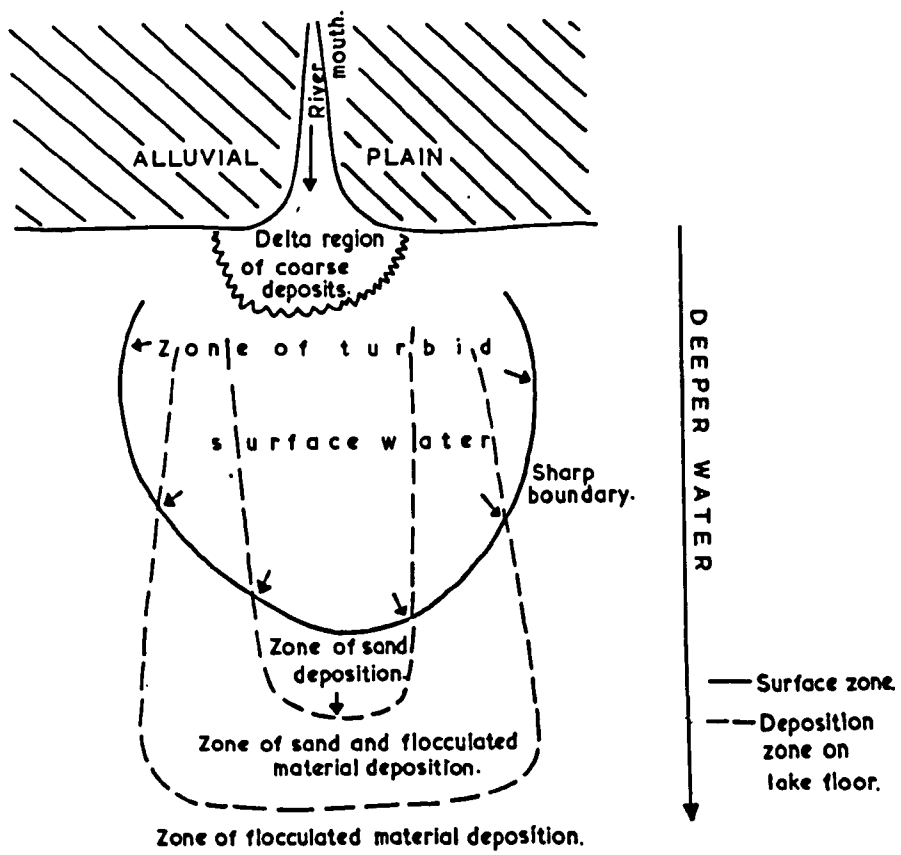


Figure 67. Hypothetical Zones of Flocculated Deposition Between River Mouth and Deep Water. (no scales given deliberately)

deposition) should not be disregarded though it would probably not be detected in the analyses in this study.

It is doubtful if a significant proportion, even of the finest fractions of Windermere material, is carried in suspension over the threshold and into the South Basin, though in lakes and reservoirs in which flocculation is not so important this tendancy is significant (Eakin, 1936).

Successive storm phases in the Post Glacial period have caused an increase in the total quantity of material accumulating on the lake floor though some redistribution takes place, particularly during each individual phase.

General Summary of the Processes of Deposition Under Examination.

It is deduced from the preceding discussion that the processes of deposition in lakes and reservoirs in which flocculation occurs, such as Windermere in the Post Glacial period, would lead to several expected observations as a result of mechanical analyses of the bottom sediments. These were all observed in Windermere during this study; the details are discussed in the remainder of this Part III. Expected observ-ations include:

a. The proportion of flocculated material to unfloccul-ated material increases away from river mouths (fig. 67); from a "sandy" zone just offshore from the delta to the middle of the lake where material was almost exclusively flocculated. The detailed variations of the sedimentary properties of both the coarse and fine groups are not anticipated. however, and are examined here with particular reference to variations in transport media and lake environments. These properties include pH, organic content, water content, and flocculation;

and particle size attributes such as median diameter, sorting, and grade mean. In this last respect Rolfe (1957) has observed, from dispersed particle size analyses, that finer deposits lie upstream from coarser deposits in Lake Mead, U.S.A.. He suggested that this is due either to the decrease downstream of the strongly flocculating smectite ("montmorin") clay mineral content, or to the fact that fine material is swept out of the dam control system at the foot of the lake.

b. Variations are more likely to occur in the sediments just offshore from the delta due to alternation of the locations of the zones (fig. 67), than in the more stratified deeper water deposits (Trask, 1951). Details of the variations with special reference to the changing zones of deposition, stratigraphically and "contemporaneously" according to the weather conditions, are examined mainly by field observations, discussed in Chapter 22, and by the sand grade proportion of the samples.

c. Shallow water deposits not off a river mouth are ephemeral and under the variable influence of wave action. Here, a normal examination of shallow water deposits allows a brief discussion only (Chapter 22).

Thus the chief topic of the following chapters in this Part of the thesis consists of an examination of the detailed variations, in different parts of the lake and at different stages in its sedimentary history, within the frame-work of these generalised depositional processes. In this respect, it is emphasised that these, as outlined here, apply particularly to the Post Glacial period and that the processes of deposition of the various Late Glacial facies, particularly the lacustrine types, are considered separately in Chapter 21.

Certain other properties (last section of Chapter 13), not given detailed examination here, are nonetheless examined in a more general sense, by providing representative data for obtaining a comprehensive understanding of lake sedimentation.

Particle Size Populations.

It has been noted that the apparent upper size limit of flocculation in Windermere material was between ø5.0 and ø5.7 (or 0.030 mm and 0.020 mm; fig. 53, Chapter 14). This is in general agreement with Sherman (1953) and with Van Andel and Posthma (1954 p.93) who claim that particles larger than 0.024 mm and 0.016 mm respectively are physically unable to enter into the flocculated state. It will be shown, in Chapter 31 in the following Part IV on qualitative analyses, that the upper size limit of hydrated clay minerals (which are taken here to represent Post Glacial alteration products of the parent rock minerals) is approximately 0.020 mm. It is tentatively suggested here that these two divisions are related to each other, in Windermere Post Glacial material at any rate, and that the hydrated clay minerals are the chief mineral content of floccules, not only being incorporated in them but actually assisting in their formation due to their hydrated and altered state. Thus this fundamental division of sedimentary particle populations is not based on grain size to the same extent as it is based on mineralogical content and associated properties such as the ability to enter in flocculation. The flocculating clay mineral population (redefined "clay" here), however, with its upper size limit of 0.020 mm, may approximately coincide with the "log normal clay population", postulated by Spencer (1963), with its median between

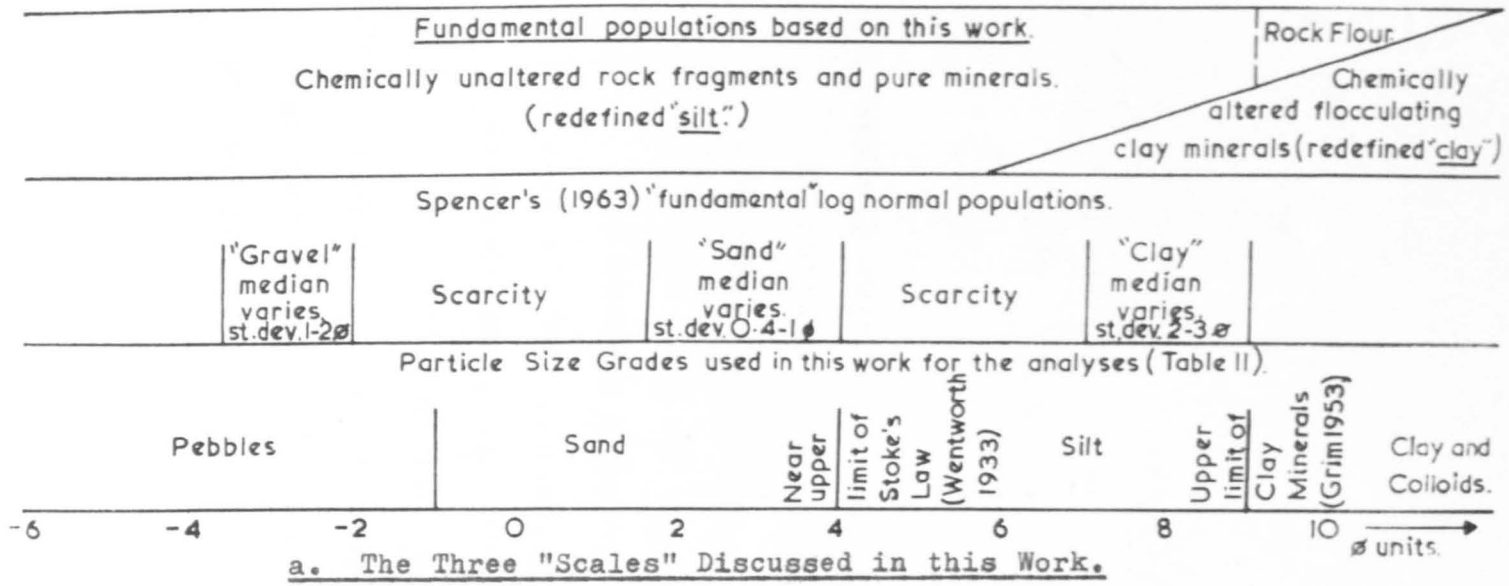
ϕ7 and ϕ9 (0.0080 mm and 0.0020 mm approximately) and a standard deviation of between 2 and 3 phi units. The unaltered rock fragment population (redefined "silt" here) may approximately coincide with the "log normal sand population" of Spencer (loc. cit.) with its median between ϕ1.5 and ϕ4 (0.350 mm and 0.064 mm approximately) and a standard deviation of between 0.4 and 1 phi unit. This last population, as postulated here (underlined above), extends below 0.020 mm, the upper limit of the former population as postulated here (underlined above). This is because mechanical weathering, particularly the glacial grinding, is able to reduce unaltered rock fragments to very small sizes though by doing so, in fact, it renders them more vulnerable to chemical attack and alteration. However, it is uncertain how the finer material in this unaltered "silt" category behaves during the flocculation phase of deposition; whether it assists the formation of floccules or merely becomes incorporated in them, or whether the particles remain discrete however fine. Spencer's "log normal sand population" appears to occur in two distinct types of deposit in Windermere: some of the beach deposits and coarse fractions of Late Glacial material contain the coarser part of the population with its median at about 0.350 mm; while lake deposits contain the finer part of the population with a median at about 0.110 mm. These two "sub-populations" rarely occur together so the importance of Spencer's category as a generalisation remains uncertain.

The two populations ("silt" and "clay") postulated here may vary according to the relative intensity of the chemical attack of the aqueous environments. Thus, in the Late Glacial

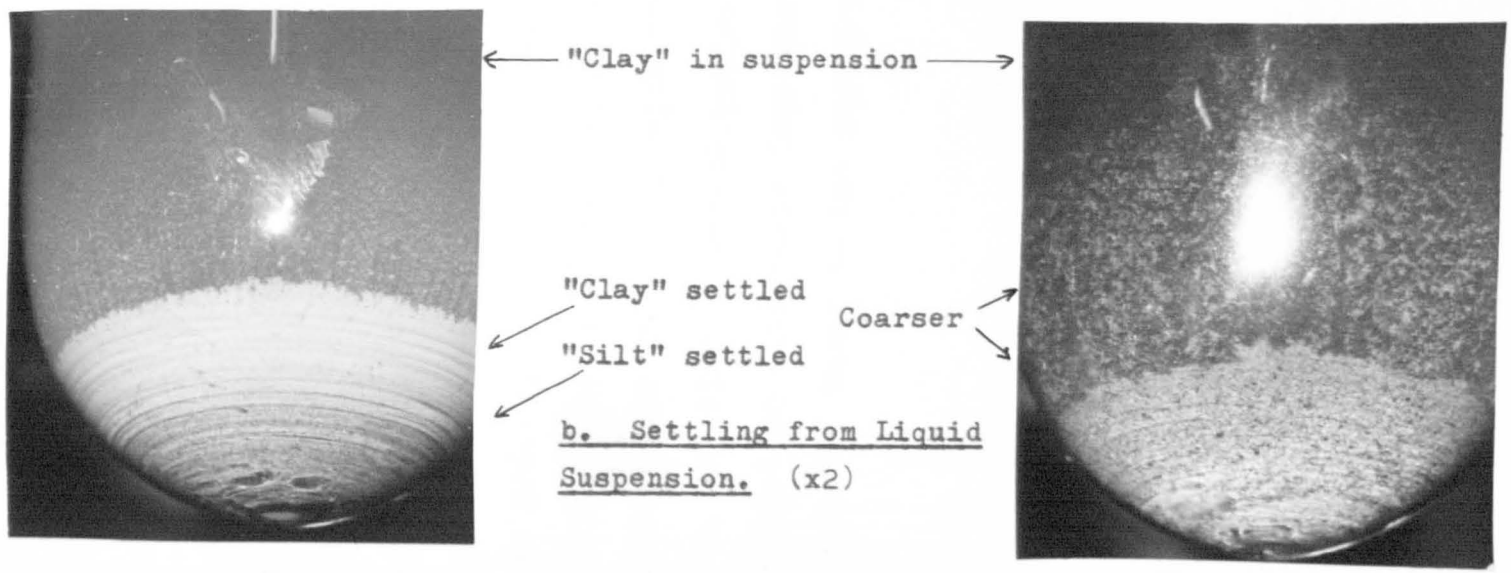
period the upper size limit of the pink clay population (Chapter 21) is probably lower than that set at 0.020 mm, which was measured from Post Glacial lake sediments. They are shown diagrammatically in comparison with Spencer's populations and with the particle size grade used here, in figure 68 a. They are easily distinguished in liquid suspension as shown with the Post Glacial and Late Glacial examples in figure 68 b. It is important that there is no confusion between these "fundamental" clay and silt populations, postulated here as a result of observations made during this work, and the grades used for size analysis (pebbles/sand/silt/clay) which are arbitrarily based purely on grain size (table 11).

Spencer (1963) claims that the postulated scarcity of material in the "silt grade" (0.0020 mm, Grim's, 1963 upper limit of clay minerals, to 0.064 mm, Wentworth's, 1933, change of aqueous sedimentation; see Chapter 10), and the fact that it does not correspond to one of his three postulated log normal populations, would invalidate the use of the triangular diagram (fig. 62). While it is admitted that the validity of such a diagram would be of greater sedimentological importance if Spencer's hypothesis is correct, there are two observations that should be made:

a. Spencer's postulated fundamental populations are by no means proven to exist beyond the realms of useful statistical concepts or "models"; largely because their origin and composition is so uncertain and because there is no suggested reason for their being log normal within a limited basin. Until these hypothetical populations are proved to exist, therefore, this greater significance cannot be placed on his



a. The Three "Scales" Discussed in this Work.



b. Settling from Liquid Suspension. (x2)

Figure 68. Populations of Sedimentary Particles.

type of triangular diagram.

b. The sand/silt/clay grade diagram as used here is perfectly valid, anyway, provided the exact significance of the diagram with respect to material being analysed is out-lined.

In the "still water grouping", the most important in figure 62, there is an estimated mean silt grade content of 55% which is hardly a scarcity (though it may be divided between Spencer's log normal clay and sand populations). Also the fact that the three apices of the triangles were size grades, rather than fundamental populations, was stressed and the exact significance of the resulting diagram was explained in Chapter 17 with figure 62. In this way, there-fore, the diagram proved useful for classifying Windermere material on this basis (see the comprehensive section in figure 63 based on the groupings in the triangular diagram.

Chapter 21 The Late Glacial Period

This chapter is divided into two sections. The first is concerned with drift material sampled outside the lake, the second with laminated facies in Windermere. These two groups are separated here because of the different principles applying to their respective sampling and analyses. They are broadly contemporaneous but were formed in different parts of the basin. Some of the implications concerning the composition of the samples are made in conjunction with some qualitative analyses in the next Part IV (Chapter 31; see sections on hydration and calcite content). The Post Glacial processes of deposition were described in Chapter 20; the Late Glacial processes are described below.

Drift; Boulder Clay and Outwash Plain Deposits

The properties of the drift are very varied and there were insufficient data to provide satisfactory representative maps or, often, data. These last are given in brackets (see Chapter 18) when available. Chi square comparisons (Chapter 18) are illustrated and P values given in brackets.

The deposition of boulder clay and its outwash plain meltwater derivatives (fluvioglacial and deltaic deposits), and the rapidly evolving Late Glacial environments, have been described in Chapter 1. The samples in this study have all been classified accordingly in Chapter 17. The drift now varies in thickness up to 100 feet.

Further sedimentological considerations, based on miscellaneous and physical results, are best discussed by examining each property in turn and noting its implications. There are points made here best illustrated by turning to the detailed list of results in Appendix No. 4 (table iii); where this is the case, the appropriate locality no. is given.

Miscellaneous Analyses

Flocculation was not measured (Chapter 14).

Organic Content

Due to the climate it is unlikely that any of these samples, except the deltaic silts, were deposited containing organic matter. Thus any organic loss on ignition is material which has been incorporated since their formation, particularly in the upper exposed layers sampled here. The rusty clays at the top of the surface sampled short cores from the threshold region (3.5%; 1.95; (5)) do not contain significantly more organic matter than all the other deposits counted together, excluding deltaic silts (3.3%; 2.25; (28)).

It is not known whether the deltaic silt facies was formed in the Late Glacial or the early Post Glacial period. The presence of significantly more organic matter ($P < 0.05$; fig. 69 a) in the silt (11.3%; 4.4; (5)) than in the clay (see above) suggests an early Post Glacial age.

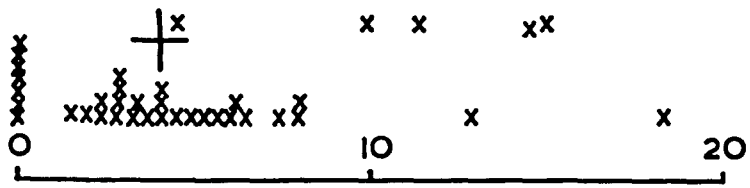
Water Content

These results are of uncertain validity (Chapter 7). It is unlikely that any of these drift samples, except the deltaic silts, were deposited with as high an interstitial water content (weight loss on drying at 95°C) as they now have. It is significant that they contain more water (43.7%; 11.75; (9)) than the lacustrine material (see below). This is due to (Post Glacial probably) post depositional alteration and consequent wetting. There may be some relationship between interstitial water and loosely absorbed molecular water driven off at about 130° (Part IV).

Figure 69. Late Glacial Non Lacustrine Material; Comparisons by Chi Square Probability Tests.

(N.B. Representative Data in Script)

a. Organic Content. %



5 Deltaic Silts.

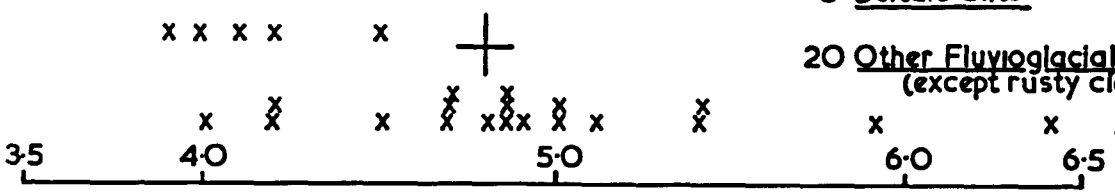
33 Other Fluvioglacial Samples.

n=38		
0 (2½)	5 (2½)	5
18 (15)	12 (15)	30
18	17	35

$$\chi^2 = \frac{4}{2\frac{1}{2}} + \frac{4}{2\frac{1}{2}} + \frac{6\frac{1}{4}}{15} + \frac{6\frac{1}{4}}{15} = 4.0 \text{ approx.}$$

$P < 0.05$

b. pH.



5 Deltaic Silts.

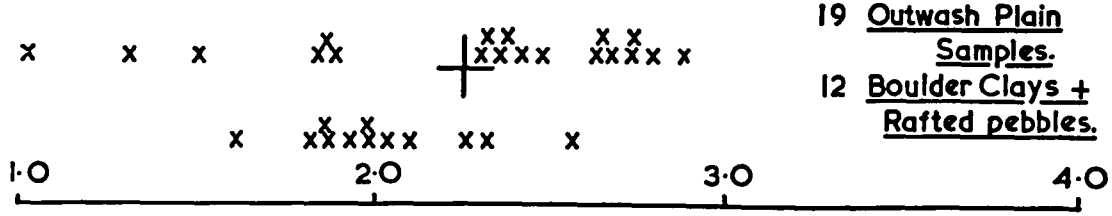
20 Other Fluvioglacial Samples (except rusty clays)

n=25		
5 (2½)	0 (2½)	5
7 (9½)	12 (9½)	19
12	12	24

$$\chi^2 = \frac{4}{2\frac{1}{2}} + \frac{4}{2\frac{1}{2}} + \frac{4}{9\frac{1}{2}} + \frac{4}{9\frac{1}{2}} = 4.0 \text{ approx.}$$

$P < 0.05$

c. Roundness No.



19 Outwash Plain Samples.

12 Boulder Clays + Rafted pebbles.

n=31		
6 (9½)	13 (9½)	19
9 (5½)	2 (5½)	11
15	15	30

$$\chi^2 = \frac{9}{9\frac{1}{2}} + \frac{9}{9\frac{1}{2}} + \frac{9}{5\frac{1}{2}} + \frac{9}{5\frac{1}{2}} = 5.2 \text{ approx.}$$

$P < 0.025$

pH

This is considered in detail in Chapter 31. However, it is thought that the original drift was approximately neutral and contained a particulate calcite fraction from the disintegration of the rocks. Thus the lacustrine deposits, which contain calcite at present, were largely derived from the drift. Subsequently, organic matter in the in situ soils on the drift and increasing interstitial water (see above) resulted in an acid environment of decomposition products. This now causes the upper layers of the drift, anyway, to be fairly strongly acidic so that they no longer contain calcite.

In this respect, the more organic deltaic silts (pH 4.1; 0.2; (5)) are significantly more acidic than the other drift samples (4.8; 0.31; (20)), noteably the clay sampled immediately beneath it at B4 and B12 ($P < 0.05$; fig. 69 b). This last category does not include the rusty clay samples which are less acidic than the other clay samples (5.75; 0.4; (4)).

The possibility that pH has changed since sampling must be realised.

Mechanical Distributions

These facies are assumed to have attained mechanical stability. The most significant work on these varying drift samples has been outlined along with the triangular diagram (fig. 62) in Chapter 17. It was shown that there are three major divisions of the drift.

Boulder Clay

This is unsorted and would probably have been scattered randomly on the diagram if there had been sufficient data. Boulder clays are widespread in the basin (fig. 63). A typical particle size distribution is shown in figure 70 a; this type of distribution is the source of most other deposits in the basin.

Running Water Deposits

Both the coarse and fine groups of particles indicate that the meltwater environment, by which the original boulder clay was being resorted and redistributed, was never ponded for a sufficient length of time for still water deposits to be dominant. The bimodal nature of most of the deposits indicates that the meltwater activity decreased throughout the period. This portion of the drift varies widely from nearly pure sand and pebbles, with a clayey matrix, to less than 15% of sand with a silty matrix. Included in this group were samples taken from the periphery of the lake, some from the threshold region, and the deltaic silts (see below, fig. 71). The curves of samples nos. 210, 217, and 194 are used to illustrate the variations (fig. 70 b, c, d).

Still Water Deposits

The fine matrix is present in sufficient proportions to indicate that the meltwater environment was ponded for a longer period of time. The coarse group of particles is generally fairly fine sand. The curves of samples nos. 187 and 188 are used to illustrate the variations (fig. 70 e, f). There were three areas where these glaciolacustrine deposits were formed. Figure 71 is equivalent to property variation

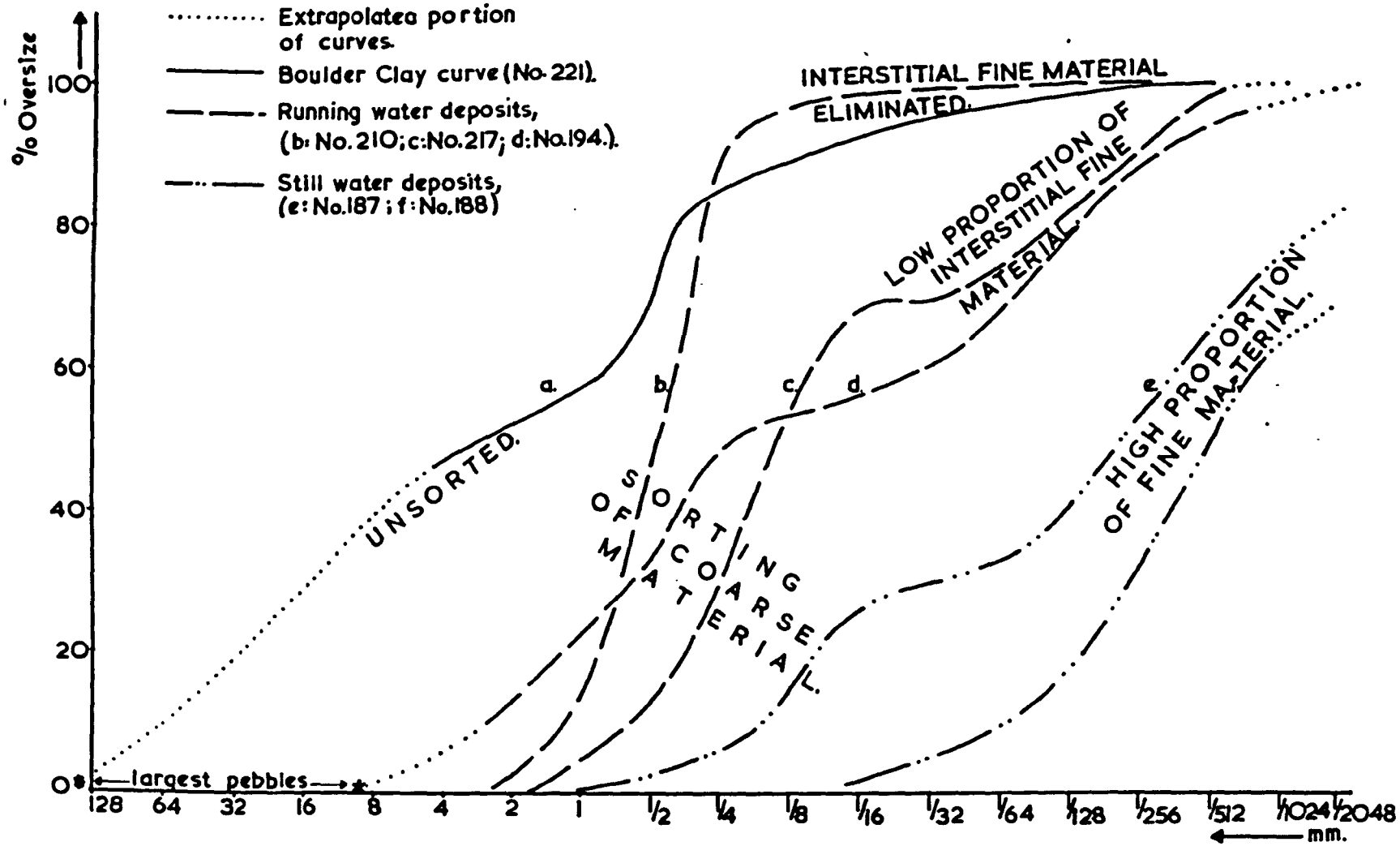
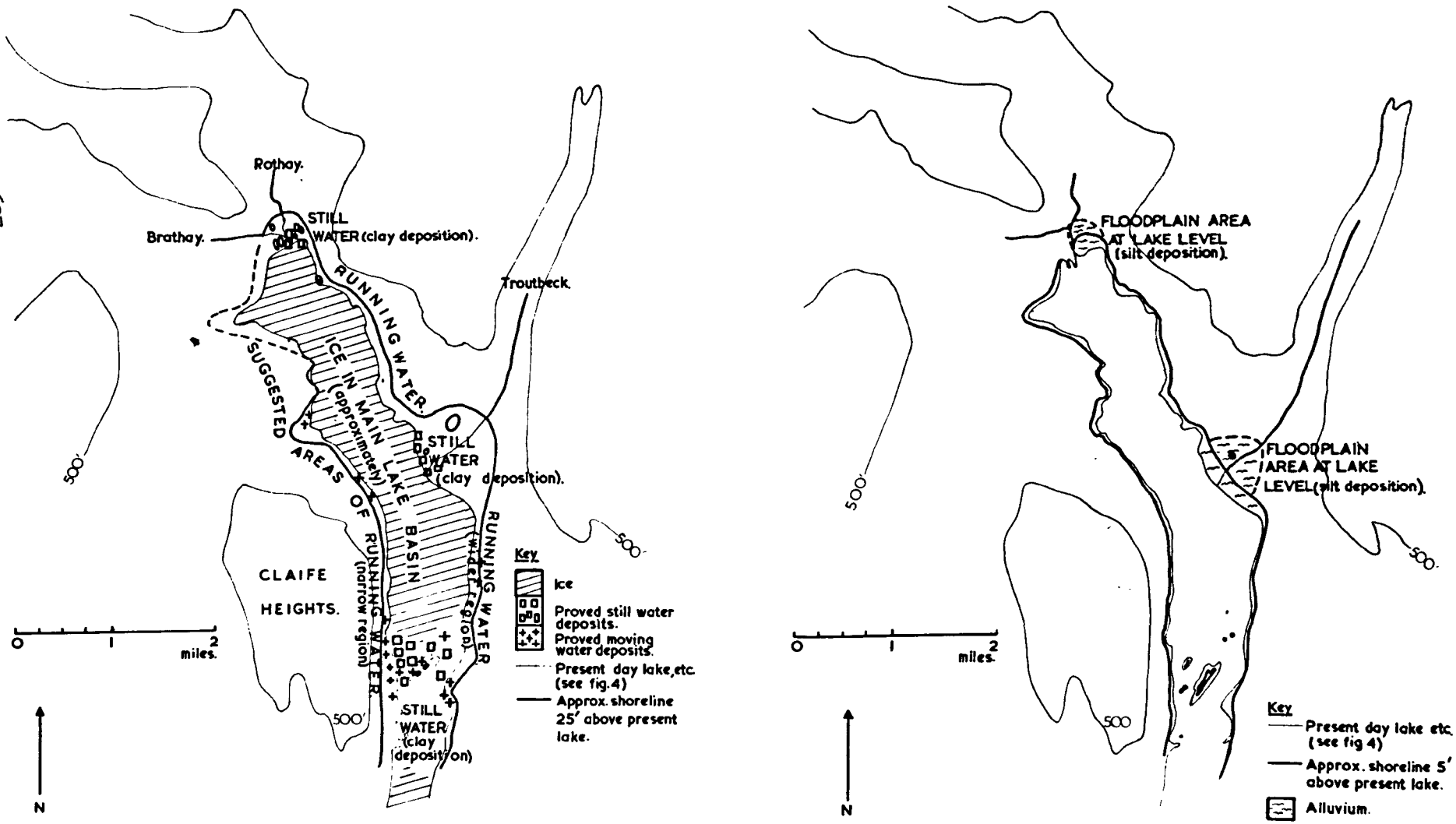


Figure 70. Illustration, by means of cumulative curves, of the redistribution of unsorted Boulder Clay (a) among the Fluvioglacial (b,c,d,) and Glaciolacustrine (e,f,) environments in the outwash plain. (N.B. Size scale is compressed so that half the angle of slope is equivalent to the same sorting value as in figure 51a)



a. Early - Middle Late Glacial; Formation of "Ponded" Deposits.

b. Late Late Glacial; "Deltaic" Silt.

Figure 71. Maps Showing Late Glacial Stages in the North Basin of Windermere.

maps. Figure 71a is a hypothetical plan of the Windermere area during the formation of these glaciolacustrine deposits. The shoreline of the meltwater channels is placed at 25 feet above the present lake level to correspond to the beach platform. Figure 71b is a hypothetical later stage when the main ice had melted and the lake level had dropped to the 5 foot platform; this was probably due to partial collapse of the natural dam at the southern end of the lake (Chapter 1).

a,b. Brathay and Troutbeck Delta Regions.

Stagnant ice in Windermere ponded the water flowing in the rivers to form small temporary lakes with water levels higher than at present (fig. 71 a). The junction between this glaciolacustrine clay (Md: 0.0053 mm; -;(2). MD: 0.097 mm; - ; (1). Grade Mean : 2.18; - ; (2)) and the coarser silt above (Md: 0.0138 mm; 0.0040; (5). MD: 0.143 mm; 0.060; (4). Grade Mean: 1.66; 0.28; (5)) is more gradual at Brathay (viz. B4) than at Troutbeck (viz. B12), suggesting that the former yielded slowly to the changed conditions when it was released. These last resulted in freely flowing rivers entering the ice free main lake, then about 5 feet above its present level, and depositing muddy material over the flood plain. This last approximately corresponds to the present flood plain. At Troutbeck, where the junction is very sharp, the lake yielded more rapidly to the changed conditions.

The clay and silt deposits sampled at Troutbeck are coarser than those from Brathay (fig. 62a). This apparently indicates that Troutbeck was generally the more active of the two rivers at that time. This may have been due to the shorter flood plain at Troutbeck; and to the absence of sediment trap lakes between the torrent course and the delta.

The smaller streams did not show evidence for ponded deposits at their inlets.

c. Threshold Region. Surface sampled clays (smooth and rusty) are generally still water deposits. It is difficult to define the extent of this Late Glacial ponded body of water, either geographically or in time, because most island and shoreline samples nearby are dominantly running water deposits (Chapter 17). Also some of the structures observed here, such as the laminated and current bedded sands and silts on Cockshott Point and Thompson's Holme, indicate a typically active meltwater environment. It is suggested that the early Late Glacial meltwater streams in the outwash plain ran along the side of the ice in the main lake (possibly more on the east due to the shadow of Claife Heights; fig. 71 a) and emptied into this shallow pond. This was dammed between the ice in the north and south basins, the high ground, and piles of outwash debris at the boundaries of the shallow region. This lake may have been released from time to time by melting ice or a clearing of debris and reformed at a later stage; or it may only have been in existence for one period.

Roundness

All the pebbles examined had undergone some degree of rounding. The boulder clay pebbles (2.12; 0.28; (6) and the rafted lacustrine bands of pebbles (1.90; 0.14; (6)) are indistinguishable statistically ($X^2 \neq 0$). They are classified together in this respect (1.97; 0.20; (12)) because neither group has undergone abrasion since the last

ice cap melted; though clearly there had been some abrasion previous to that. The outwash plain deposits were classified together as the early generations of sediment derived from the boulder clay by meltwater. It was therefore expected that their roundness (2.32; 0.41; (19)) should be significant-ly more marked, due to abrasion during redistribution, than the boulder clay and lacustrine pebbles ($P < 0.025$; fig. 69c).

Shapes of the pebbles were not considered here so that the "crucial recognition of a boulder clay deposit" cannot be made (Pettijohn, 1957).

Lacustrine Deposits.

Normal Late Glacial lacustrine deposition, after much of the stagnant ice had melted, was involved with the high rates of meltwater erosion of drift (Chapter 1) and with the winter freeze and spring thaw alternations. Thus normal thinly graded annual varves were formed. Slumping of these occurred spasmodically in limited areas (Smith, 1959b). This was due to gravity slipping over lubricated planes down steep slopes, set off either by further melting of ice in the deeper parts of the basin and/or by critically strong influxes of turbidity currents. It is then suggested that either local landslides outside the lake and rapid erosion, or this slumping, caused the water in the corresponding parts of the lake where the thinly laminated fac-ies were taken up by the active conditions to be turbid causing the formation (redeposition) of coarser grey silt passing up into pink clay. These occur in localised bands which may be up to three or four inches thick. It is these abnormal bands which were analysed here so the sedimentological data do not repres-ent normal deposition. They are of interest, however, because

they represent general lakewater activity.

Pennington (1955) counted approximately one thousand varves in the Late Glacial sequence. This indicates a period for these waterlain deposits of about a thousand years between the deposition of the moraines on the valley floor and the influx of organic matter 10,800 years ago (Chapter 22) at the beginning of the Post Glacial period. This makes a total of about 12,000 years of lake deposition in Windermere. The valley moraines were never penetrated by the corer in the present work.

As with the drift deposits in the previous section of this chapter, further sedimentological considerations based on the miscellaneous and physical results are best discussed by examining each property in turn and by noting its implications. A summary of the variations appears in Chapter 23. It is important to note that the sampling of these sediments was complicated by the slump structures.

Miscellaneous Analyses.

Flocculation.

This was not measured (Chapter 14). It is thought that flocculation was unimportant in the Late Glacial period and that the small mineral particles generally settled discretely.

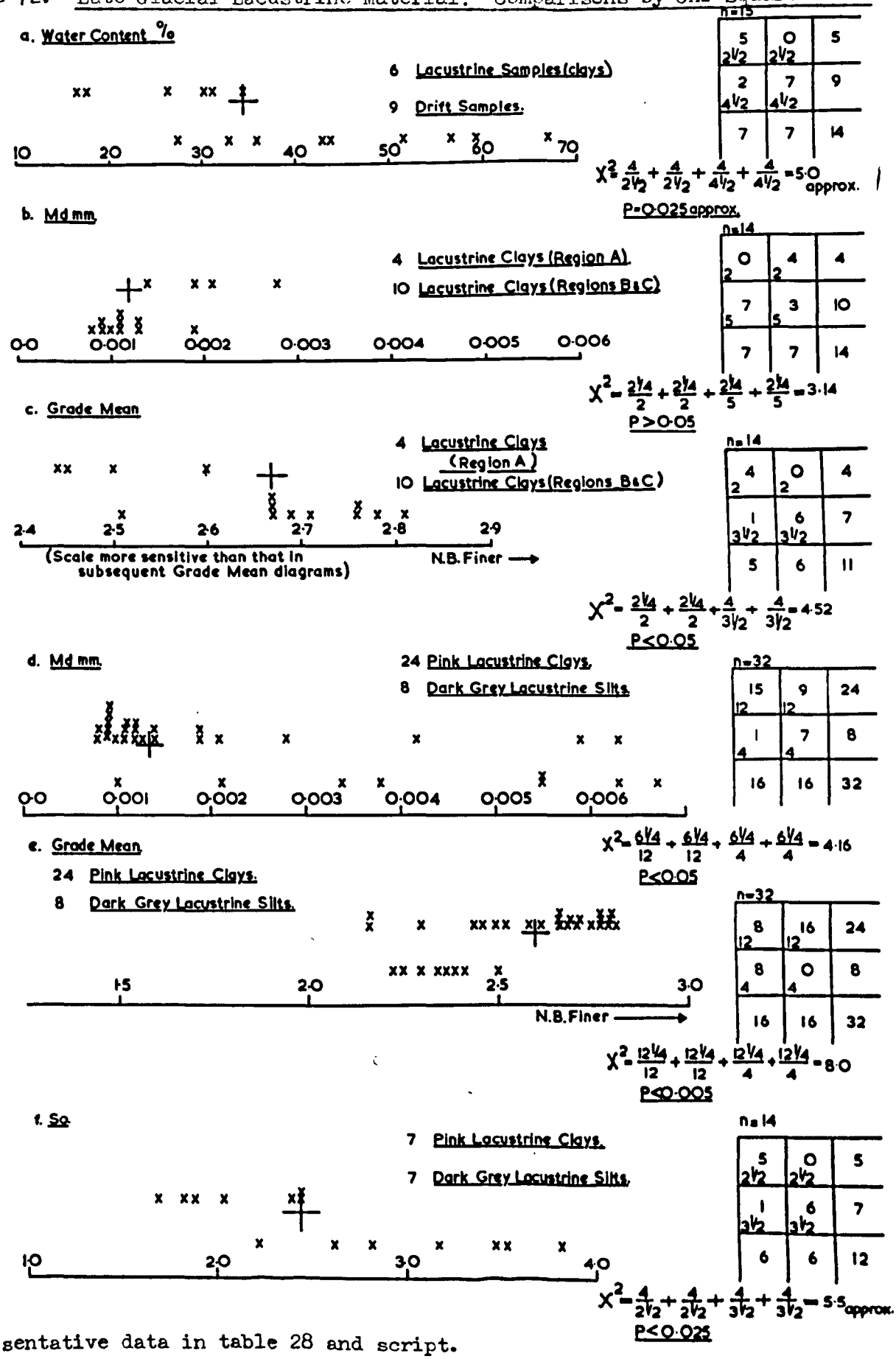
Organic Content.

There is no organic loss on ignition in any of the lacustrine samples as they were derived from a bare drift terrain.

Water Content.

These results are of uncertain validity (Chapter 7). They contain significantly less interstitial water (28.3%;7.2; (6, all pink clays)) than the drift (see above) from which they were derived ($P = 0.025$; fig. 72a). Pennington (1947a) claims that

Figure 72. Late Glacial Lacustrine Material: Comparisons by Chi Square tests.



Representative data in table 28 and script.

the clays contain 35% water. This is probably due to the post depositional compaction in the lake and also to their buried environment protecting them from weathering. Thus, slumping apart, it was expected to find that water content decreased with depth of burial (viz. C7, C8).

pH.

Unfortunately all these samples were too compacted for insertion of the probe for pH measurement. However the qualit--ative analyses (Chapter 31) indicate that the silt fractions of lacustrine material are of similar general content to the rocks and are only altered in that a proportion of the calcite has been removed by the chemical environment. Also that the clay fractions are considerably altered and contain no calcite. From these it is inferred that the Late Glacial lake environment was very slightly acidic and that lacustrine material has been protected from further chemical attack to the present day. This is in contrast to the exposed Late Glacial drift material (see above).

Mechanical Distributions.

These facies are assumed to have attained mechanical stability. They are considered in three separate sections. However, it will be shown that they are all composed of clay fractions (< 0.002 mm) with similar mineral and chemical contents. These are probably altered from the original rocks; also they contain no calcite but are slightly hydrated. They are, in fact, the Late Glacial equivalent of the redefined "clay" fundamental population (Chapter 20, fig. 68). Their upper size limit is probably lower than 0.020 mm due to limited chemical attack in the Late Glacial, in contrast to the Post Glacial sediments (Chap--ter 22). The silt fractions (0.002 - 0.064 mm) of the pink clay

and dark grey silt facies, though different from the clay fract--ions, are similar to each other. They are equivalent to an appropriate mixture of the original unaltered rock types though calcite has been reduced. Thus they are the Late Glacial equiv--alent of the redefined "silt" population. These two are the most common of the lacustrine facies so this uniformity suggests that the main difference between the pink clay and the dark grey silt is the proportions in which the coarse and fine mineral types are mixed. The visible and textural distinctions are due to the mechanical grading during the formation of these beds. A graded bed has a unimodal mechanical distribution (size here) at any given level (see below).

The silt fraction of the less common light grey sand facies are different from the others (a second Late Glacial equiv--alent of the redefined "silt" population) though their clay frac--tions are the same. This suggests that the rare phases of stronger Late Glacial lakewater activity caused an influx of this different coarser material. These qualitative results are more fully explained in Part IV and, of coarse, they are deduced only from those samples analysed during this study. A more compreh--ensive study involving, say, hundreds of Late Glacial lacustrine samples may have shown a more complex situation.

a. Pink Plastic Textured Clay Facies.

This includes pure non organic clay bands in the transitional clay/gyttja sequence for convenience. It consists of samples in which pink clay mineral material (see above) appears to be domin--ant. An asterisk (*) below refers to a pink clay band in gyttja.

It has been shown that some samples were erroneously distinguished as pink plastic clay (Chapter 17, fig. 62a). These were, in fact, narrow varves in which the pink clay material,

while appearing predominant, was mixed with much coarser material. However, for statistical purposes it is necessary to include these "poor" samples with the rest because the entire facies was sampled on the arbitrary basis of its appearance, so that no distinction is justified at a later stage because of subsequently obtained data. Also none of the three lacustrine facies are entirely pure (see below) so any distinction between them would have to be arbitrary.

A further point is that the finest samples (those which approached the pure mineral state) gave results which allowed only the median diameter to be calculated (see the notes on the lower limit of application of the Sedimentation Balance in Chapter 13). Thus, though the representative data (table 28) include sorting, skewness, and kurtosis, these last values were probably derived from the "poor" coarse samples mentioned above. Also they made the representative Md value slightly high. The representative curve is shown in figure 73a.

The triangular diagram (fig. 62a) has most of these clay sample points near to the clay apex in the still water grouping. Stratigraphic variations are complicated by erroneous sampling and slumping. However the Md values and Grade Mean values from localities C3, C6, C7, C12 indicate that the clay gets coarser up the cores. It is doubtful if these are significant by any statistical criterion as the relationship is not reproduced in the other cores examined. So values indicate better sorting up the core at C3. Geographical variations are tested, using the four Regions of the lake (see figure 19 and Chapter 19), by comparing, in this case, all the Md and Grade Mean values from C3 (samples nos. 145 - 148; Region A) with those from C6, C7, and C9, and C12 (samples nos. 142*, 150; 151, 152; 144*, 155, 156; and 157, 158,

Table 28. Representative Data for Late Glacial Lacustrine Facies.

Data	Pink Clay	Dark Grey Silt	Pale Grey Sand	
			Unimodal	Bimodal
Md (mm)	0.0012;0.0005;(24)	0.0565;0.0018;(8)	0.016; - ;(2)	0.0099;0.0022;(3)
So	2.05;0.31;(7)	3.19;0.46;(7)	2.20; - ;(2)	2.53;0.88;(3)
Sk	0.89;0.15;(7)	0.48;0.14;(7)	0.73; - ;(2)	0.77;0.42;(3)
k	0.245; - ;(2)	0.23; - ;(1)	0.245; - ;(2)	0.23; - ;(2)
MD (mm)				0.106;0.0020;(3)
SO				1.17;0.02;(3)
SK				1.07;0.04;(3)
K				0.22;0.01;(3)
Sand %				26.0;12.0;(3)
Clay %				16.0;2.0;(3)

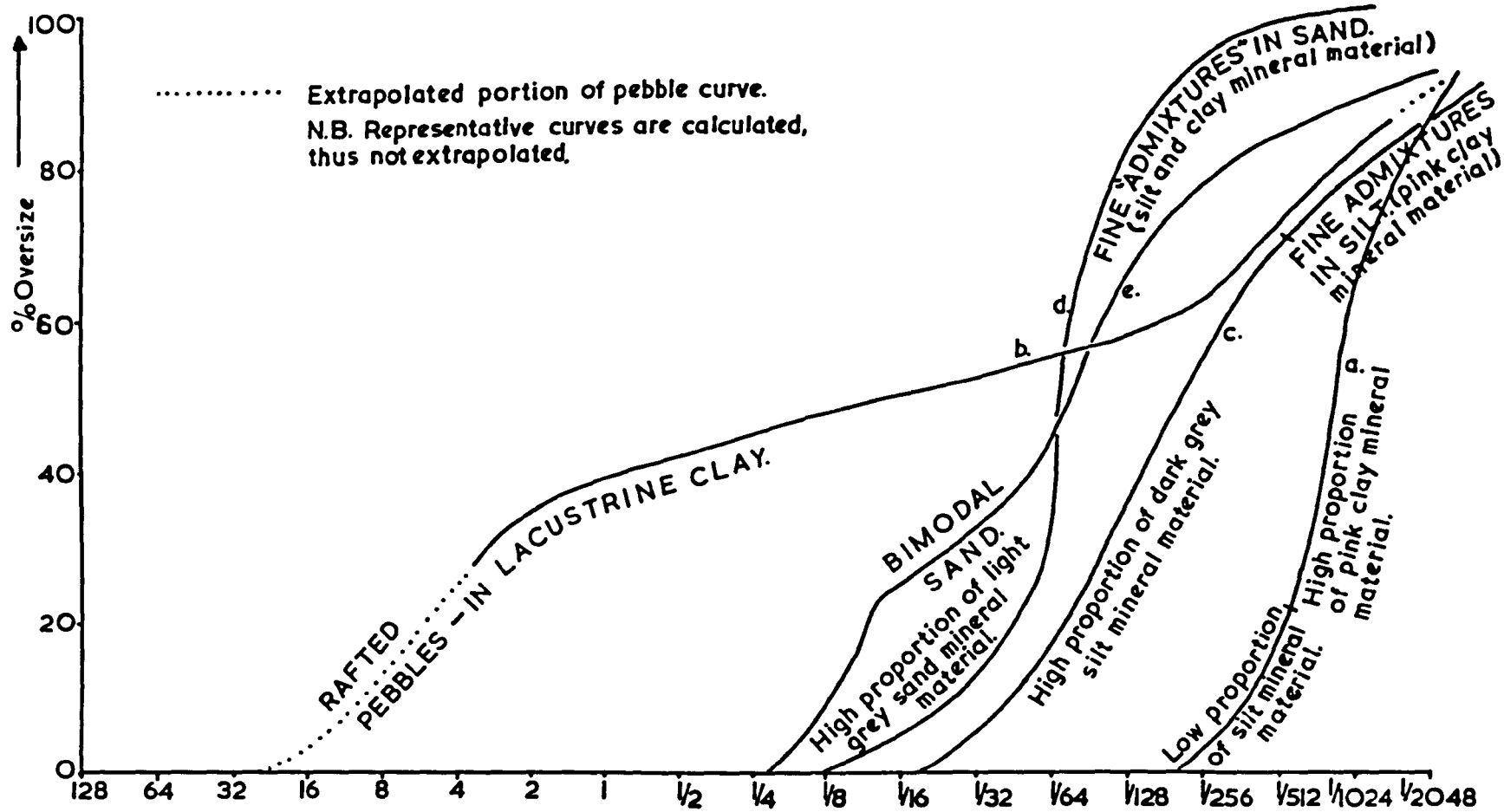


Figure 73. Representative Cumulative Curves for Late Glacial Lacustrine Facies.

(N.B. Size scale is compressed so that half the angle of slope is equivalent to the same sorting value as in figure 51a)

159; Regions B and C respectively). The tests (fig. 72 b, c) show that coarseness decreases downstream (from Brathay only). The Grade Means in Region A are significantly coarser than those in Regions B and C counted together ($P < 0.05$). But the relat-ionship for Md values is not quite proved ($P > 0.05$). The clays are comparatively well size sorted because they are comparatively pure with respect to their pink clay mineral population content.

In the pebble bands the representative Md/MD ratio is (0.00055;0.0006;(6)). This extremely marked bimodality is ill-ustrated in figure 73b (sample no. 148/181). It indicates dep-osition by dropping from a floating raft of slowly melting ice. Pettijohn (1957, p.275) claims that rafted pebbles are among the most positive indications of glacial deposition in an area. Also as expected, at C3 where pebble samples nos. 179, 180, 181 were taken from the same core, there is a marked decrease in the coarse-ness of the pebbles in the younger bands due to the waning of the ice influence.

b. Dark Grey Silt Facies.

This consists of samples in which the dark grey silt ~~min-eral~~ mineral material appears to be dominant. The triangular diagram (fig. 62a) shows these samples to be in the middle of the still water grouping along the clay - silt edge. The repres-entative data for the dark grey silt facies (table 28) is ill-ustrated in figure 73c. As expected this is significantly coarser than the clays (Md: $P < 0.05$; Grade Mean: $P < 0.005$; fig. 72 d, e). The silt is also significantly poorer sorted than the clays ($P < 0.025$; fig. 72f) due to varying clay "admixtures".

Variations within the dark grey silt facies, both strat-igraphic and geographical, are difficult to assess due to inad-equate data.

c. Light Grey Sand Facies.

This consists of samples in which the light grey coarser population is dominant and the finer clay is the same as before. The triangular diagram (fig. 62a) shows these "fine sandy lake deposits" to be either outside the still water grouping and near the silt - sand edge, or in the "overlap zone" at the coarse end of the still water grouping. The term "sand" is clearly misused here because the samples generally consist of predominantly silt grade material. However, it was originally used because of the friable appearance of the facies and the term is still useful as a distinction. Of the five samples two are unimodal when the coarse and fine fractions are combined and three are bimodal. Representative data (table 28) for both these types are illustr-ated in figure 73 d, e. There were insufficient data to prove that the sands are significantly coarser than the silts and clays. The distributions suggest that these active lakewater deposits are extremely varied. Unimodal samples probably approximately rep-present the original coarse material, while the poor sorting and negative skewness suggest that finer material was "admixed" at a later stage when conditions were quieter. These fine "admix-tures" became even more important in the bimodal samples.

Flocculation was never important in the deposition of any of these graded and "admixed" facies as it was in the Post Glacial.

Roundness.

The rafted pebbles were classified with boulder clay (see above).

Chapter 22 The Post Glacial Period

This chapter is divided into three sections. The first is concerned with gyttja and associated deposits sampled in Windermere; this period of deposition, though it occupied most of the Post Glacial, is termed "early Post Glacial" for convenience. The second section is concerned with property variations over the ooze/gyttja boundary and a general discussion on the change of deposition. The third section is concerned with present day deposits, surface ooze sampled from Windermere itself and from the three small lakes, near shore silts from shallow water, and beach material. Thus the two main groups, which are considered separately here because of the different principles applying to their respective sampling and analyses, are stratigraphically from different periods though they are all lake deposits. Again in this chapter, some of the implications concerning organic matter and pH results are made in conjunction with the qualitative analyses in the next Part IV (Chapter 31).

Early Post Glacial Deposits

These occupy most of the sequence of organic muds in the lake and generally lie conformably over the Late Glacial lacustrine sequence (see discussion of Pennington's work, 1947a, in Chapter 2). The boundary between them is sharp, representing a sudden influx of organic detritus into the lake as a result of climatic amelioration. The sequence has been zoned by Pennington (loc. cit.; also see figure 7); the pollen zones are correlated with the general climatic evolution of northern England since the last ice age. The lower part of

the sequence is the "transitional series", in which the org-
-anic gyttja is interspersed with occasional pure pink clay bands, and the uppermost boundary of which is a comparatively thick clay band taken as contemporaneous all over the lake. These were a result of landslides, or equivalent catastrophic events, spasmodically charging the streams with an abnormally pure mineral load (Pennington, 1943). For purposes of stratigraphical correlation, however, the sampling for this work did not use these zones. Instead specific "levels" (Chapter 4) were measured in all the cores on the assumption of uniform rates of deposition, first for the transitional series and then for the gyttja. Pennington (1955; see also figure 7c here) has calculated the unit mass of sediment accumulating per unit area of the lake floor at present. Assuming that this mass was deposited in unit time throughout the latter part of the Post Glacial period, the author has calculated that the 4 metres depth (approximately) of gyttja above the top clay band was deposited over a period of 8150 years. The 1.5 metres (approximately) of the transitional series beneath the top clay band, assuming double the later rate, was deposited over a period of about 2500 years. This adds up to a total of 10,650 years for "early" Post Glacial deposition. It has been explained that these two rates of deposition varied from place to place but were taken as constant at each locality. This is indicated by the fact that the thickest Post Glacial sequences (> 5.5 m.) occur at localities C1 (core no. 1) and C10 (core no. 3) off Brathay and Troutbeck respectively. The top clay band is generally between 3.5 and 4.5 metres from the top; and the Late Glacial

laminated clays between 4.5 and 5.5 metres from the top (fig. ii, Appendix No. 2).

There are four major levels, A, B, and C are in the upper gyttja sequence, and D is in the transitional series. In addition to these, the cores from C7 and C8, two closely neighbouring localities, were sampled more closely as a check on this method of sampling and on the subsequent analyses. In these two cores, levels e and f are between A and B, levels g and h are between B and C, and level i is in the transitional series between C and D. These levels may be regarded as conformable strata for the purposes of this study. Table 29a shows the main early Post Glacial samples' numbers listed with their levels, locality nos., and Regions.

This check on this method of sampling, unfortunately, was not entirely successful. It was hoped that all the nine samples from C7 would correlate closely in every respect with the nine from nearby C8, thus "proving" that the levels were accurately assessed and that the analyses were reproducible in practice. However, the core from C8 exhibited evidence for slumping and distortion in the transitional series (core no. 11, fig. ii), accompanied by an increase in grain size and organic content of the corresponding gyttja layers (i and D levels, table 29b). The levels above this portion appeared to correlate fairly closely with each other suggesting that the method used was, in fact, satisfactory.

For purposes of geographical correlation, the lake has been divided into four arbitrary Regions; these have been disucssed in Chapter 19 and were illustrated in figure 19. The core from locality C8 was omitted from Region B for most

Table 29. Correlation of Core Gyttja Samples.

a. Sample Nos. with Locality Nos. and Regions.

Gyttja	Locality Numbers														
	A				B					C				D	
Level	C1	C2	C3	C4	C5	C6	C7	*C8	C9	C10	C11	C12	C13	C15	C17
A	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
e	-	-	-	-	-	-	127	128	-	-	-	-	-	-	-
f	-	-	-	-	-	-	129	130	-	-	-	-	-	-	-
B	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
g	-	-	-	-	-	-	131	132	-	-	-	-	-	-	-
h	-	-	-	-	-	-	133	134	-	-	-	-	-	-	-
C	103	-	104	105	106	107	108	109	110	111	112	113	114	115	116
i	-	-	-	-	-	-	135	136	-	-	-	-	-	-	-
D	-	-	117	-	118	119	120	121	122	-	123	124	-	125	126

b. Comparisons of C7 and C8.

Level	Md (mm)		Grade Mean		Organic Content (%)	
A	.0044	.0047	2.24	2.31	18.3	19.6
e	.0043	.0039	2.29	2.27	13.5	16.1
f	.0046	.0040	2.29	2.25	19.8	21.2
B	.0030	.0039	2.40	2.28	37.6	22.1
g	.0043	.0044	2.31	2.75	20.4	22.8
h	.0044	.0050	2.26	2.24	20.9	20.7
C	.0043	.0043	2.24	2.30	19.0	20.7
*i	.0026	.0060	2.43	2.20	14.9	21.6
*D	.0029	.0068	2.39	2.20	15.5	21.9

* Uncertain Data due to presence of thick clay band (script

of the tests because of the uncertainty of its results. Surface sampled gyttjas were omitted for most of the tests, stratigraphic and geographical, due to their uncertain mechanical stability (see below) and to uncertain correlation with the A level gyttja from the cores. Also these last were taken from the threshold in contrast to the cores and this would create non representative groups of gyttja samples. These surface sampled gyttjas were, however, considered in relation to the ooze/gyttja boundary (see below).

There were three other less important early Post Glacial facies examined. Three pink clay samples from the transitional series, two of which were the topmost clay band; these were considered with the pink clay lacustrine facies for convenience (Chapter 21). Three pale grey sandy samples, which were found in irregularly occurring thin layers in different cores, were also examined. Two "coky" samples from a blackish layer about 50 cms from the top, which occurred in most of the cores examined; their origin is uncertain but their comparatively recent age (fig. 11) indicates that they may be related to a period of forest fires caused by early man.

Further sedimentological considerations, based on miscellaneous and physical results, are best discussed by examining each property in turn and by noting its implications. A summary of the variations appears in Chapter 23.

Miscellaneous Analyses

Flocculation

Flocculation was not important in the late Glacial sediments (see below), but it became so in Windermere at the beginning of the Post Glacial. The phenomenon has not been

successfully reproduced in the laboratory but the measure of it is taken to be approximately proportional to the degree of flocculation that took place just prior to the deposition. A proportion of the gyttja gave "negative"data; this probably means that the amount of flocculation that took place during laboratory examination was weak enough to cause the loosely held floccules to settle more slowly than the same material dispersed, due to their extreme porosity and low specific gravity (Sherman, 1953). These results are a measure of weak flocculation in the lake. Also many of the samples exhibited maximum flocculation at sizes smaller than 0.002 mm; these were not measured accurately; some of the "negative" results may be in this category. These data were, however, included in the examination of results though they took the form of that percentage of flocculation observed at 0.002 mm (Chapter 14).

Stratigraphic Variations. The representative data are listed in table 30a; from these it appears that the degree of flocculation became stronger in the younger gyttja, though this relationship was not proved ($P = 0.075$; fig. 74a). Also levels A, B, C, and D show a consistent downward decreasing trend; there is one chance in 4! (Factorial 4 = 10) random examinations that this relationship would be observed; this is equivalent to a probability of 10% ($P = 0.010$).

Geographical Variations. The representative data are shown in figure 75a; it is also shown that Region B gyttja exhibited a significantly lower degree of flocculation than Regions A, C, or D ($P < 0.005$, fig. 74b); while Region A appears to exhibit the highest degree. Flocculation was not measured for the minor facies.

Table 30. Representative Data of Gyttja Facies.

a. Miscellaneous Properties.

Gyttja Level.	Percentage Values			
	Flocculation	Organic Content	Water Content	pH
A	10.0; - ;(15)	18.3;2.25;(15)	64.8;8.75;(7)	5.65;0.47;(9)
e	9.8; - ;(2)	14.8; - ;(2)	64.8; - ;(2)	5.45; - ;(2)
f	16.5; - ;(2)	20.5; - ;(2)	67.6; - ;(2)	5.50; - ;(2)
B	8.5;6.3;(15)	21.1;3.80;(15)	66.7;2.25;(9)	5.60;0.18;(8)
g	12.0; - ;(2)	21.6; - ;(2)	68.0; - ;(2)	5.55; - ;(2)
h	- ; - ;(2)	20.8; - ;(2)	67.1; - ;(2)	5.50; - ;(2)
C	3.0; - ;(14)	20.5;1.25;(14)	64.7;3.35;(8)	5.65;0.16;(10)
i	- ; - ;(2)	18.0; - ;(2)	67.6; - ;(2)	5.40; - ;(2)
D	neg.; - ;(10)	17.7;2.30;(10)	67.9;10.4;(5)	5.70;0.20;(7)
Black.		13.0; - ;(2)	. .	
Total Facies.			66.5.	5.60.

b. Mechanical Properties.

Gyttja Level.	Sand (%)	Md (mm)	So
A	1.6;1.7;(15)	0.00405;.0012;(15)	2.60;.41;(13)
e	1.4; - ;(2)	0.00410; - ;(2)	2.76; - ;(2)
f	0.8; - ;(2)	0.00430; - ;(2)	2.63; - ;(2)
B	1.9;0.8;(15)	0.00400;.0007;(15)	2.57;.22;(11)
g	1.0; - ;(2)	0.00435; - ;(2)	2.57; - ;(2)
h	1.0; - ;(2)	0.00470; - ;(2)	2.38; - ;(2)
C	1.4;0.9;(14)	0.00400;.0008;(14)	2.35;.28;(10)
i	0.5; - ;(2)	0.00430; - ;(2)	2.28; - ;(1)
D	0.6;0.5;(10)	0.00345;.0011;(10)	2.24;.18;(7)
Black.		0.00560; - ;(2)	3.10; - ;(2)

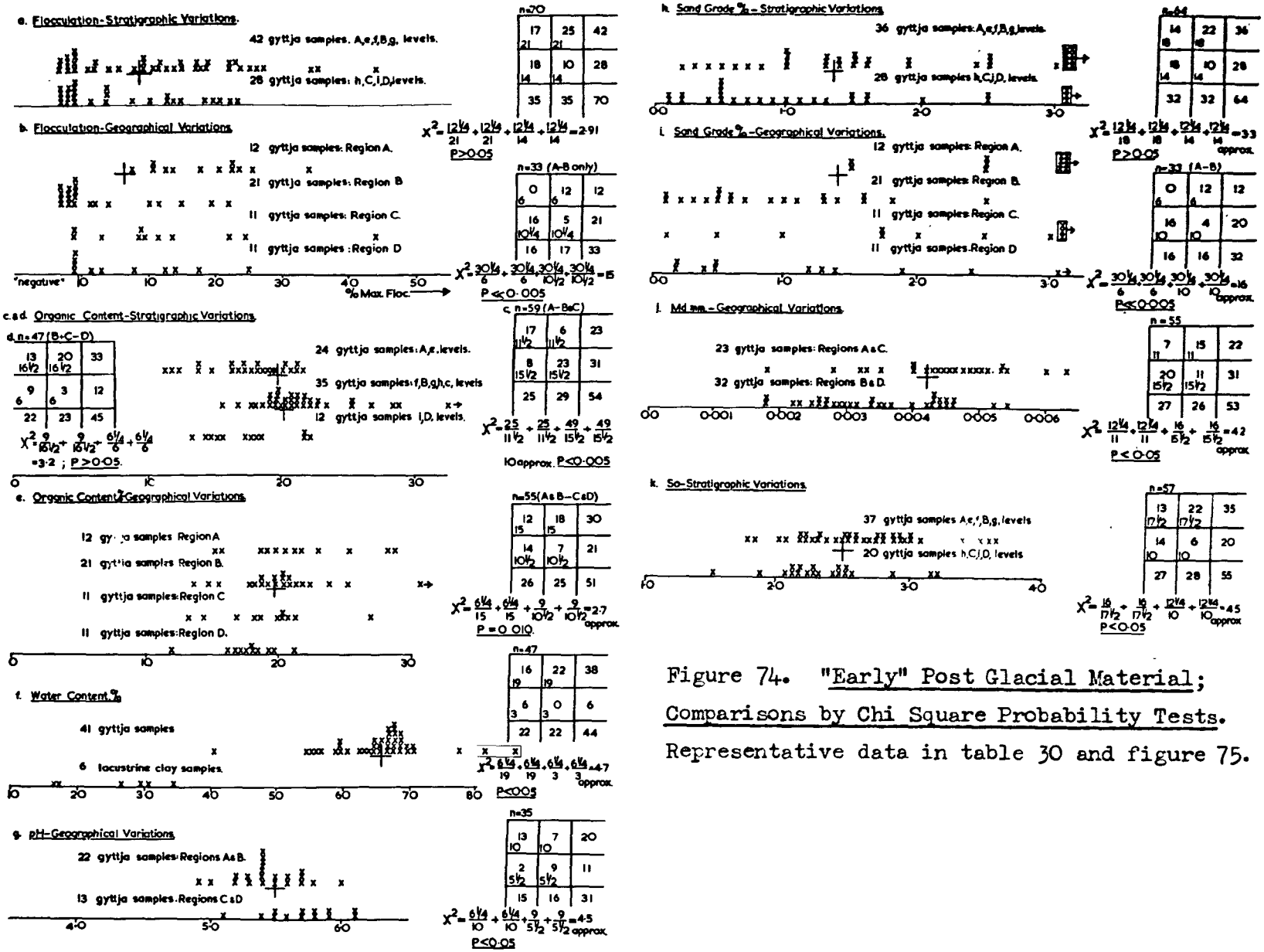


Figure 74. "Early" Post Glacial Material; Comparisons by Chi Square Probability Tests. Representative data in table 30 and figure 75.

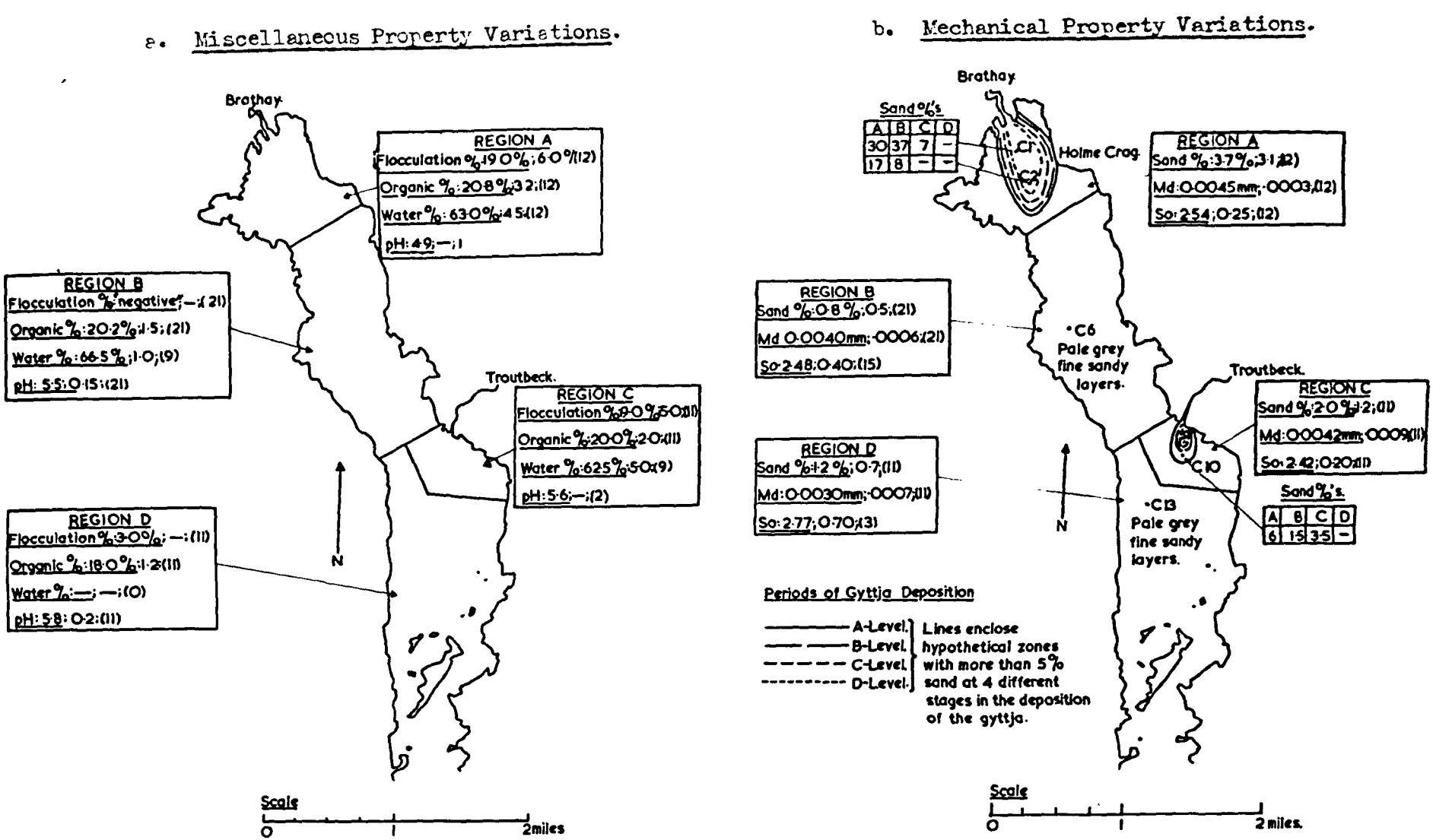


Figure 75. Property Variations Maps of the North Basin of Windermere: Representative Data for Gyttja.

N.B. No distinctions are made for the different levels ("facies") due to insufficient data.

Statistical comparisons in figure 74.

Pennington (1943, 1947a) has suggested that freshly formed floccules are composed of mineral grains, algal cell walls, and small organic particles in a "polysaccharide gel matrix"; and that this matrix is attacked by bacteria after burial with the result that there is partial breakdown of the floccules (Richardson, 1941, also suggested this). This effect may increase in the earlier deposits if bacterial attack remains active and may thus tend to cause reduced flocculation to be measured in the laboratory.

Size at which Maximum Flocculation occurs

This is a complex property of a sample involving both its grain size distribution (Chapter 23) as well as its degree of flocculation. It is uncertain how important a property this is and the significance of the results is difficult to assess. Out of the 70 gyttja samples analysed, not one exhibited maximum flocculation at a size greater than 0.0055 mm (contrast this with surface ooze, see below).

Organic Content

Pennington (1943, 1947a) claims that the organic content of the Post Glacial lake deposits remains approximately constant at about 20%. However, variations were observed here and may be significant.

Stratigraphic Variations. The representative data are listed in table 30a; from these it appears that the organic content of the two oldest gyttja levels is lower than that of the middle levels but that it is reduced again further up. Data from gyttja levels A and c were counted together and gave significantly lower results than the gyttja samples from levels f, B, g, h, and C, ($P < 0.005$; fig. 74c). These

latter data, however, were not proved to be higher than those from levels D and 1 ($P > 0.05$; fig. 74d).

Geographical Variations. The representative data are shown in figure 75a; from these, it appears that Region A gyttja contains a slightly higher proportion of organic matter than the others, which have a decreasing proportion in the order B, C, and D. However, these relationships were not confirmed statistically (fig. 74e).

The two black "coky" samples, with the coke fragments removed, had an organic content lower than the gyttja levels (table 30a).

Water Content

Pennington (1943, 1947a) claims that the water content of the Post Glacial lake deposits decreases from 85% in the surface ooze to 35% in the Late Glacial clays. It has already been mentioned that these results in this work are of uncertain validity (Chapter 7). It was shown, however, that the results dropped significantly over the gyttja/clay boundary ($P < 0.05$. fig. 74f).

Representative data for both stratigraphic and geographic variations and for the full facies group are shown in table 30a and figure 75a respectively. There are no trends of either sort exhibited by this property.

The minor facies were not examined in this respect.

pH

The significance of pH values in the general context of lake environments is discussed more appropriately in Chapter 31. It was unfortunate that a comparison could not

be made, in this respect, between the Post Glacial gyttja and the Late Glacial lacustrine material due to the compact-ness of the latter when sampled (Chapter 21). The possibil-ity that pH has changed since sampling, due to oxidation of sulphides to sulphuric acid (Mackereth, personal communication 1963; also see Chapter 20), must be realised.

Stratigraphic Variations. The usual representative data, also that for the full facies group, are listed in table 30a; there are no trends exhibited by this property.

Geographical Variations. The representative data are shown in figure 75a; there appears to be a slight trend of decreasing acidity downstream from the main inlet at Brathay. This relationship is confirmed statistically ($P < 0.05$; fig. 74g).

The minor facies were not examined in this respect.

Mechanical Distributions

The buried gyttja facies is assumed to have attained mechanical stability so that the grain size distrib-ution is no longer liable to be altered by changes in the lake. It is studied here as representative of the transport and settling conditions prior to final burial.

Richardson (1941) and the present author (Chapters 7 and 15; also see fig. 58) have shown that the particle size distributions of material before and after ignition were comparable for the same material, and that the organic content of Windermere sediments did not occur as a separate mechanical group. Thus these particle size analyses were performed after removal of organic matter.

Particle Populations. These various "early" Post Glacial facies are considered separately below. However, in the next Part IV on qualitative analyses (Chapters 30 and 31) it will be shown that the gyttja is entirely composed of similar "clay" and "silt" populations. All the gyttja clay fractions have similar mineral contents (in contrast to the surface ooze, see below) which are altered, by strong hydration particularly, from the parent rocks and contain no calcite. These are, in fact, the Post Glacial "organic" equivalent of the redefined "clay" fundamental population (Chapter 20, fig. 68); they occur up to a size of 0.020 mm (contrast this with the Late Glacial "clay" population, Chapter 21). The silt fractions, again with similar mineral contents, are probably equivalent to an appropriate mixture of fragments from the unaltered parent rock types, though calcite has been removed. These are, in fact, the Post Glacial equivalent of the redefined "silt" fundamental population.

The clay bands in the transitional series, like the Late Glacial deposits, are non organic and only slightly hydrated. The thin pale grey sandy layers are also non organic, they contain calcite, and are completely non hydrated. This is an important demonstration of the extent to which chemical alteration of detrital material is controlled by the presence of organic matter in a deposit; this is discussed in Chapter 31.

The triangular diagram (fig. 62a) showed the majority of these early Post Glacial deposits to be in the still water

grouping and near to the clay - silt edge of the triangle (the "coky" samples, of uncertain sedimentary origin, were not plotted). The exceptions to the above rule were two gyttja samples with a high proportion of sand from near Brathay mouth, and the three thin sandy layers. These were classified as "fine sandy lake deposits" for convenience (Chapter 17) and were assumed to have been deposited in exceptionally active lakewater conditions.

Zones of deposition. The general processes of Post Glacial deposition in the lake have already been considered (Chapter 20). The proportion of discrete sand is high near the river mouths and it decreases away from here accompanied by an increasing proportion of fine material; this floccul-ates when the conditions are sufficiently sluggish and settles with a unimodal natural distribution. The gyttja is generally classified as a still water deposit because the proportion of fine material is high. It is important to assess the actual positions of these zones of deposition (sketched hypothetically in figure 67). In this respect, there are only two cores off Brathay at localities C1 and C2 which contain more than 5% sand for their entire length, and only one at Troutbeck (this last one, at locality C10, in fact only contains 6% in the A level gyttja, beneath this there is less than 5%). Thus, the sandy zones appear to have been close to the river mouths, and the fine flocculating material rapidly became dominant.

The only evidence for stratigraphic variations in the actual positions of these zones within the gyttja is the fact

that the sand proportion at localities C1, C2, and C10 increases upwards suggesting that the sandy zones were successively closer to present positions of the two main river mouths and their deltas; probably due to the fact that the deltas were being built out. This is supported by the archaeological view on the position of the Roman Camp (Chapter 1) which was thought to have been built at the water's edge but which is now several hundred yards (metres approximately) away. The occurrence of the localised thin layers of pale grey sand can only be explained by the spasmodic and localised occurrence of unusually far reaching but narrow zones of high water velocity. These are not sufficiently widespread to demand modifications to the above zones of deposition. All these considerations are summarised in figure 75b.

The sand grade percentage in the gyttja deposits was studied for stratigraphic and geographical variations, regardless of the positions of the above zones. The Grade Mean was not examined in detail because it has already been incorporated, in effect, into the sand/silt/clay triangle; and because sand grade is again being examined here on its own.

Stratigraphic Variations. The representative data are listed in table 30b; from these there appeared to be a slight increase of sand in the younger gyttja; the increase was not quite proved statistically.

Geographical Variations. The representative data are shown in figure 75b; the four Regions are plotted separately in figure 74i. Here it is seen that Region A gyttja contains significantly more sand than Region B ($P < 0.005$),

as expected due to its proximity to Brathay mouth (fig. 75b). It is also seen that this is in contrast to Region C, close to Troutbeck mouth, which, though it appears to contain more sand than Regions B or D, is not proved to do so. This is because the samples in Region C are very varied in this respect.

Variations in the Mechanical Properties of "Early" Post Glacial Deposits.

Gyttja.

Having established the zones of deposition and the varying proportions of sand in the gyttja, the variations of its mechanical properties are examined. Unfortunately, the relationship of the coarser discrete distribution to the natural settling distribution of the largely flocculated material is not fully understood due to insufficient data (Chapter 20). Thus, it can only be said that there appears to be a tendancy for the particle size of the sand to become slightly coarser away from river mouths; this is not supported statistically. The variations of sorting, skewness, and kurtosis were not understood for the above reasons, though skewness was generally positive as expected. There were no clear stratigraphic variations in this discrete group.

Fine Fraction.

The representative data for all the main Windermere Post Glacial deposits, (gyttja and surface ooze counted together), are as follows:

Md :	0.0041 mm;	0.00045;	(102)
So :	2.54;	0.35;	(86)
Sk :	1.00;	0.17;	(86)
k :	0.28;	0.025;	(13)

The variations of Md and So are considered separately below. Due to the subtlety of Sk and k, they are not examined in detail (Chapter 20). Assuming that the mathematical bias, tending to make Sk positive, remains approximately constant throughout these samples, a positive Sk value indicates that there were few mineral colloids present to give a negative bias; and a negative Sk value indicates that there was a higher proportion of these very fine particles. The variations of Sk values, however, appeared to be random and the fact that the median Sk value is 1.00 indicates that neither bias was significantly more important than the other. The value of k, 0.28, indicates that these curves were less peaked than the log normal distributions. This is not understood but it may be related to the sudden flocculation that occurred in these particles just prior to deposition.

All the representative curves for Post Glacial material are drawn with no skewness and a kurtosis of 0.28 (see below; figs. 76 and 79).

Median Diameter

This represents the discrete coarseness of the fine material just prior to flocculation and consequent deposition (Chapter 20). MD remains comparatively constant so that Md/MD is little more than a measure of Md and is not examined here.

Stratigraphic Variations. The representative data are listed in table 30b; from these it appears that, like the organic content of this facies, the coarseness of the gyttja increased from the earliest Post Glacial stages to a maximum at around the B level stage and above that it decreased in the younger layers. This is not supported statistically.

Comparison with the Late Glacial lacustrine facies showed that the Post Glacial facies (including ooze here) were almost identical in coarseness to the dark grey silt facies; they were therefore significantly coarser than the pink clays (see below) and finer than the light grey sand.

Geographical Variations. The representative data are shown on figure 75b; from this it appears that gyttja from Regions A and C, off Brathay and Troutbeck mouths respectively, are coarser than the two zones B and D in the middle of the lake. Statistical tests confirmed this general relationship ($P < 0.05$; fig. 74j).

Sorting ("Dispersion")

This does not represent the natural settling dispersion; rather it represents the amount of flocculation that took place (inverse ratio, see Chapter 20).

Stratigraphic Variations. The representative data are listed in table 30b; from these it appears that So values increase from the oldest to the youngest gyttja; this was confirmed ($P < 0.05$; fig. 74k). This supports the conclusion that flocculation has increased throughout the Post Glacial

(see above).

Comparison of all Post Glacial facies with the Late Glacial lacustrine facies, using the $n^{\frac{1}{2}}$ test (Chapter 17; also see David, 1953) and the Post Glacial median value for sorting (2.54) as "standard", indicated that the pink clays were significantly better sorted than the Post Glacial material (Chapter 21). The dark grey silts were poorer sorted, though this relationship was not confirmed statistic-ally.

Geographical Variations. The representative data are shown in figure 75b; from these it appears that Region A gyttja is better sorted than Region B; this is not confirmed statistically in contrast to the geographical variations of gyttja flocculation (see above).

Two representative curves are illustrated here for the gyttja facies itself (fig. 76); these are of Region A gyttja (a) and Region B gyttja (b), the latter contains slight-ly more sand and is slightly coarser.

Thin Pale Grey Sandy Layers

The localities of these three samples and their vatiations are not understood due to the lack of data. A representative curve (sample no. 139) is illustrated in figure 76c. The sandy portion appears to be a slightly coarser and calcite bearing (see below, Chapter 31) form of the sand in normal Post Glacial lake deposits, both differences suggesting rapid transport and burial. The fine portion gives an ex-ceptionally intense negative skewness to the distribution (Sk = 0.14), due to subsequent fine, organic free, "admixtures".

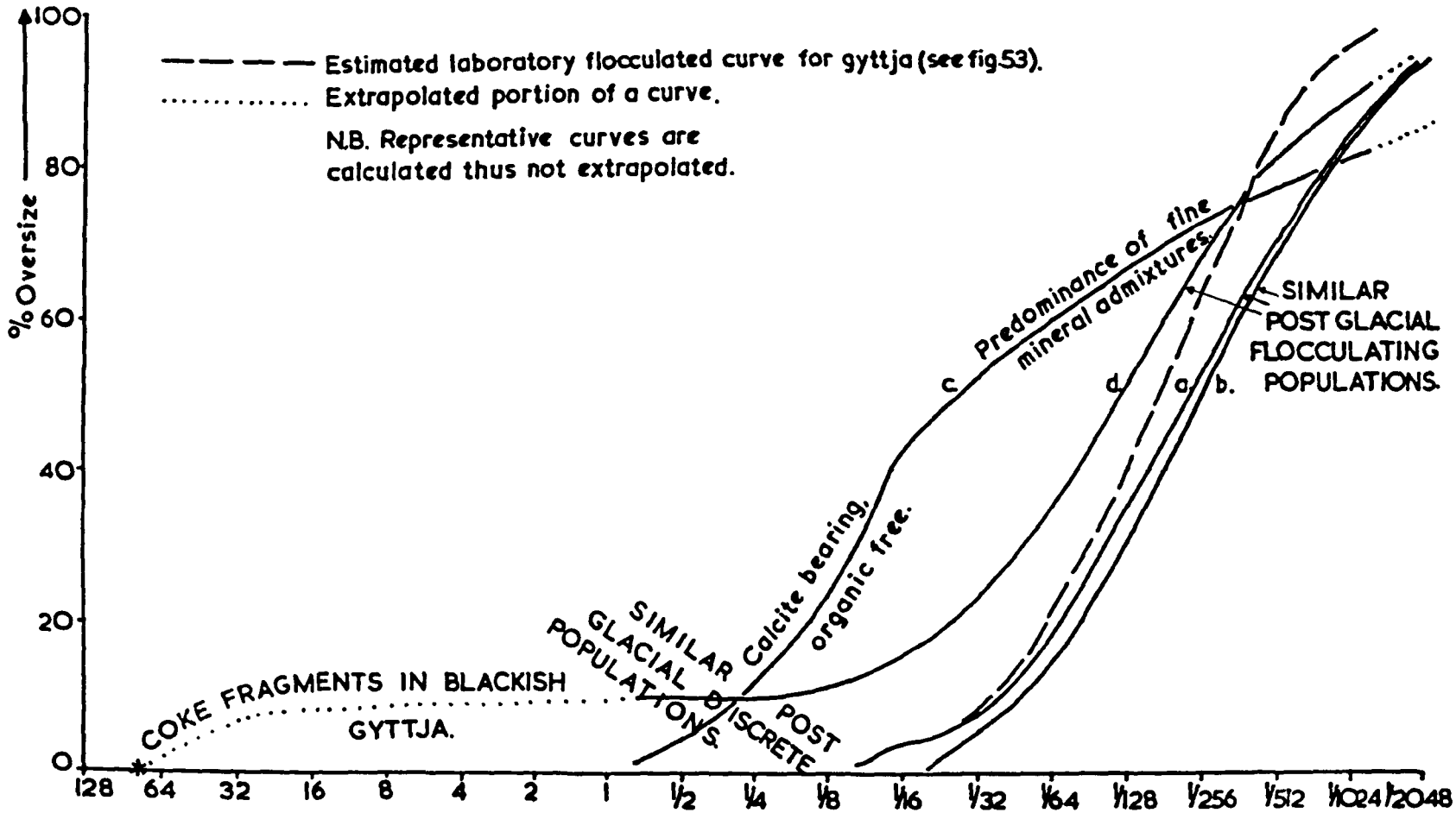


Figure 76. Representative Cumulative Curves for "Early" Post Glacial Lake Sediments. (N.B. Size scale is compressed so that half the angle of slope is equivalent to the same sorting value as in figure 51a)

Black "Coky" Layers (Table 30b)

The coke fragments are light, angular and bulky; they give a marked bimodality to the distribution curves of these samples (sample no. 140 is illustrated in fig. 76d), which would otherwise have been indistinguishable from normal gyttja. The coke and the black colour of the accompanying deposit suggest windborn ash from forest fires (see above).

A Discussion on the Surface Ooze/Gyttja Boundary

This junction has been described in Chapters 2 and 4. The surface ooze is often found in two portions; the upper is semi liquid, dark brown to black, and flocculating; this passes gradually down into a dark grey semi plastic material. These two together have been found in thicknesses of up to a foot. Black ooze normally overlies the reddish gyttja with a sharp boundary. Pennington (1943, 1947a) claims that the ooze is a later, separate, deposit, showing normal superposition; and that the differences are caused by the changed lake chemistry as a result of human settlement. This change made conditions suitable for the flourishing growth of the large diatom Asterionella which has suddenly become extremely abundant (Chapter 2). This is similar to the conclusions of Murray (1956, work summarised in Chapter 2), working on Lake Mendota.

The main results of the present work do not indicate whether or not the ooze is a separate deposit because its mechanical and mineral properties are similar to gyttja. The limnological analyses performed here are uncertain in this respect.

The following paragraph is a summary of the variations

in the short cores which included Trip 2 surface ooze (April-May, 1961) and A level gyttja from the following localities (with sample nos.): C1(9/66), C2(10/67), S11(11/81), S18(14/82), S21(15/83), S22(16/84), and S25(17/86). Flocculation does not exhibit stratigraphic trends at these localities, though the larger groups, Trip 2 ooze and A level gyttja, indicate that flocculation becomes more important in the surface ooze (see below). The organic content of the Trip 2 ooze was significantly lower than the A level gyttja (see below); this relationship is confirmed in the six southernmost short cores taken here. The pH of the two facies are similar to each other. The sand proportion was higher in the gyttja than in the ooze just off Brathay mouth (C1, C2); south of this, however, each pair of samples has almost identical sand contents; this is supported by the representative data for the two larger groups (see below).

Richardson (1941) claims that grain size decreases downwards over the ooze/gyttja interface in Windermere due to:

a. Chemical and bacterial activity breaking down "aggregates" of silt and organic detritus after burial (see above; also Pennington, 1947a).

and/or b. Fine particles settle through the large "crumbs" and come to rest beneath them.

In the present work, however, the main concern was with dispersed grain size (see below); there was found to be no fixed rule in this respect because ooze varies from time to time. Trip 2 ooze is finer than the others so that the median diameters of both the fine and the coarse groups of material deposited near the main inlet at Brathay are coarser

in the gyttja than the ooze. The two facies become more similar in these respects further south; though generally the larger A level gyttja group is coarser than the larger Trip 2 ooze group (see below). The ratio of median diameters is higher in the A level gyttja than in the Trip 2 ooze suggesting that the fine material was more affected by the stronger lakewater activity than the coarse material. The sorting of the fine material is generally better in the gyttja (see below) and particularly near Brathay. The sorting of the coarse material is similar throughout. The skewness and kurtosis variations are apparently random.

Thus it is estimated, on the basis of these analyses, that ooze and gyttja may be from exactly the same facies. The main alterations by the new environment were chemical and hence biological; this is supported by the fact that the most significant sedimentological changes across the ooze/gyttja boundary are an upwards increase in flocculation and a decrease in organic content. Mechanical properties would not be expected necessarily to change as a result. The implications of this boundary, with respect to the Late Quaternary evolution of lake sedimentation, are outlined in Chapter 23.

The Surface Ooze and Present Day Deposits

These "facies" were examined for the sedimentation processes just prior to sampling, which varied with the prevailing weather conditions, so that the nature of the ooze varies accordingly (Chapter 4). The entire length of the ooze column in each short core was collected together as one sample, however, because it was impossible to distinguish at which point the mechanically stable compact lower portion

passed upwards into the unstable semi liquid portion. It was this last portion that was of importance to an examination of "present day" processes; it was thus considerably "diluted". Ooze "facies" were collected on several occasions and may thus be regarded as giving "stratigraphical" as well as geographical variations.

a. January 1961, during cold but comparatively dry weather (Trip 1). F.B.A. Automatic Surface Sampler.

b. April-May, 1962, during warm and dry weather (Trip 2). F.B.A. Automatic Sampler. Also A level gyttja (see above).

c. August, 1962, from Windermere during floods (Trip 5). F.B.A. Automatic Sampler.

d. August, 1962, from the three small lakes before floods (Trip 5); Jenkin Surface Sampler.

Beach material and near shore silts were sampled once only, during June, 1962 (Trip 4), when the weather was damp but not stormy.

Mundie (1955) and Pennington (1955) have examined present rates of sedimentation by suspending catchment vessels and discs respectively at various levels in the lake. Pennington showed that 2.6 mm thickness of sediment (containing 93% water, 4% mineral matter, organic detritus, and living organisms) was deposited in one year (1941-1942) on the lake floor in the middle of the North Basin. Assuming uniform deposition (see above), the same author has calculated that the surface ooze represents a period of the last 135 years. The thickness of the ooze varies from over one foot near the river mouths to less than half an inch on the threshold.

For purposes of geographical correlation of the

surface ooze in Windermere, the lake was divided into the same four Regions (see above). Table 31 shows the ooze samples only tabulated with their locality nos. and the Regions in which they have been placed for detailed study. The sampling of the three different ooze "facies" was not satisfactorily representative in the different Regions. This is because it was not realised immediately that the ooze varied from time to time.

Further sedimentological considerations, based on miscellaneous and physical results, are best discussed by examining each property in turn and noting its implications A summary of the variations noted appears in Chapter 23.

Miscellaneous Analyses

Flocculation

See above for analytical limitations.

Stratigraphical Variations. The representative data are listed in table 32a; it appears from these that flocculation became strongest in the youngest ooze (August, 1962), though this has not been confirmed.

Flocculation of the Windermere ooze samples, counted together, is significantly higher than that of the gyttja samples ($P < 0.005$; fig. 77a). Pennington (1943, 1947a) has suggested that the gel matrix of the floccules in the surface ooze, in contrast to those in the gyttja (see above), have only been subjected to bacterial disintegration for a comparatively short time. It may be for this reason that the ooze gives stronger flocculation in the laboratory than the gyttja; and/or because natural flocculation is stronger

Table 31. Correlation of Windermere Ooze Samples.

Trip 1.	Region A	Region B	Region C	Region D
Locality Nos.	S1 S2 S3	-	-	S30 S32 S37 S38 S40
Sample Nos.	1 2 3	-	-	4 5 6 7 8
Trip 2.				
Locality Nos.	C1 C2	S11	S14 S15	S18 S21 S22 S25
Sample Nos.	9 10	11	12 13	14 15 16 17
Trip 5.				
Locality Nos.	S4 S5 S6	S7 S8 S9 S10	S16	S17 S19 S20 S23
Sample Nos.	18 19 20	21 22 23 24	25	26 27 28 29

Table 32. Representative Data of Present Day Facies.

a. Miscellaneous Properties.

Ooze "Facies"	Percentage Values		
	Flocculation	Organic Content	pH
Trip 5	28.2; 7.4;(12)	17.4;1.60;(12)	5.95;0.52;(12)
Trip 2	22.0; 3.9;(8)	12.4;2.50;(9)	5.40;0.55;(7)
Trip 1	17.5;15.7;(8)	17.3;3.55;(8)	
Grasmere	32.5; 6.0;(3)	23.6;3.05;(3)	6.60;0.40;(3)
Rydal W.	31.0;10.0;(3)	23.3;1.40;(3)	6.60;0.40;(3)
Elter W.	8.0;12.0;(3)	31.7;1.70;(3)	5.60;0.45;(3)
Near Shore Silts.			5.60;0.35;(3)

b. Mechanical Properties.

Ooze "Facies"	Sand (%)	Md (mm)	So
Trip 5	4.4; 3.0;(12)	0.00415;.0004;(12)	2.57;.44;(12)
Trip 2	11.5;10.0;(9)	0.00210;.0003;(9)	3.07;.47;(8)
Trip 1	2.2; 5.3;(8)	0.00445;.0011;(8)	2.50;.23;(7)
Grasmere	2.1; 4.2;(3)	0.00560;.0010;(3)	2.67;.95;(3)
Rydal W.	2.2; 9.3;(3)	0.00420;.0016;(3)	2.09;.23;(3)
Elter W.	12.9; 3.3;(3)	0.00810;.0004;(3)	2.45;.08;(3)
Near Shore Silts.	70.4;35.0;(3)		

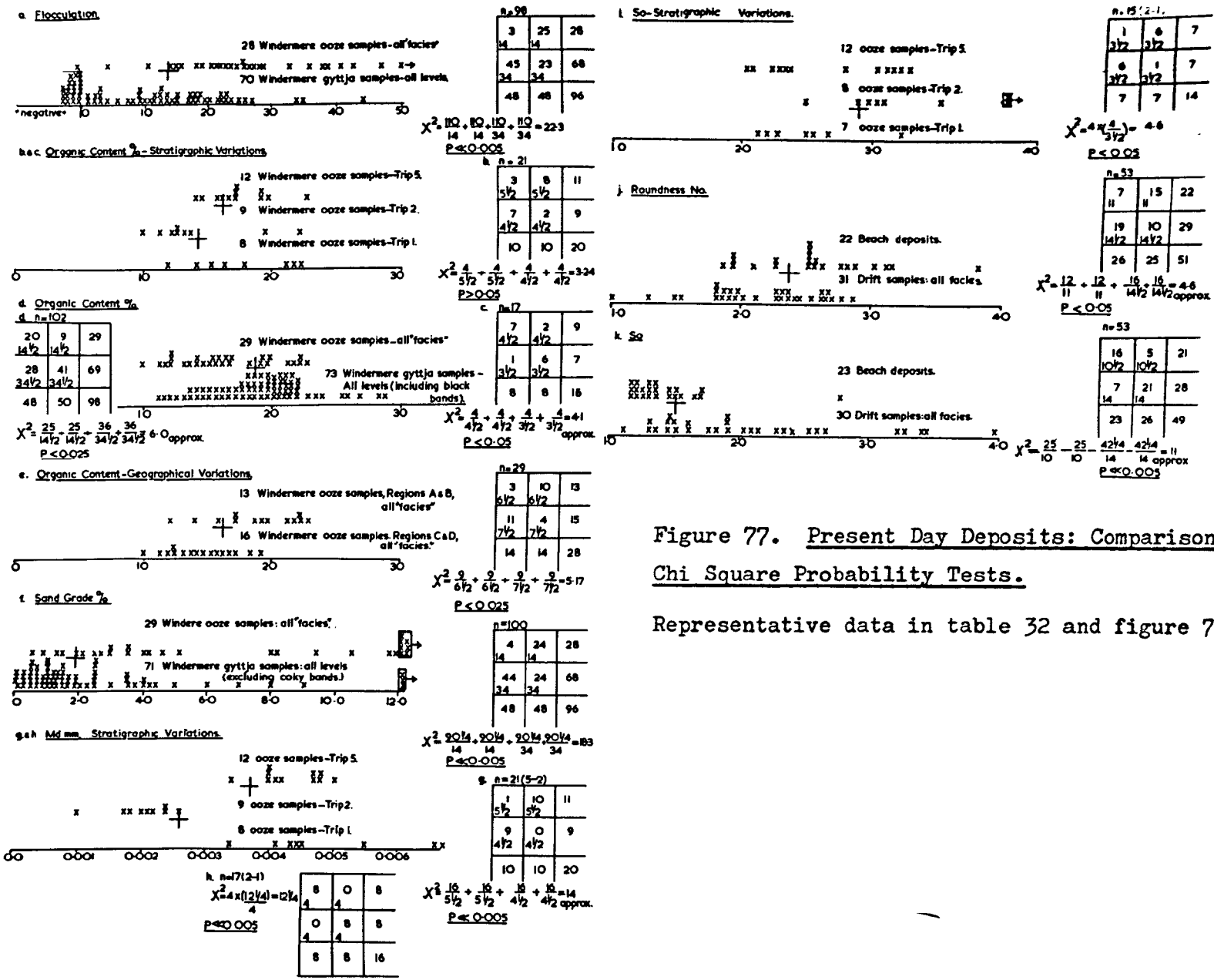


Figure 77. Present Day Deposits: Comparisons by Chi Square Probability Tests.

Representative data in table 32 and figure 78.

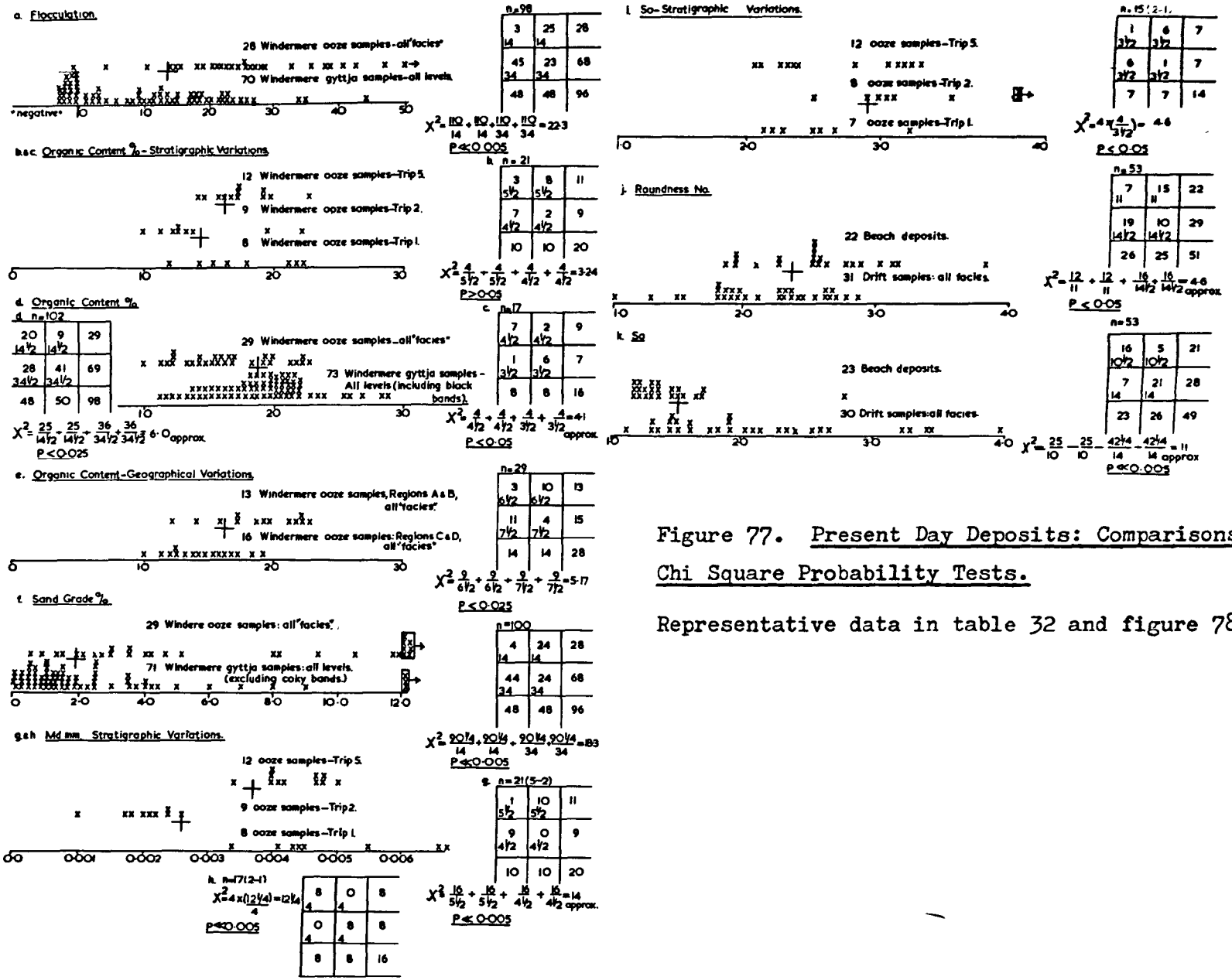


Figure 77. Present Day Deposits: Comparisons by Chi Square Probability Tests.

Representative data in table 32 and figure 78.

due to the increased sewage content of the lake. These aspects are considered in Chapter 23.

Geographical Variations. The representative data are shown in figure 78a; from these it appears that flocculation decreases downstream from the main inlet at Brathay. This is not supported statistically.

Flocculation appears to be stronger in Grasmere and in Rydal Water ooze than in Windermere; and weaker in Elterwater (table 32a).

Size at which Maximum Flocculation occurs

Out of the twenty nine ooze samples from Windermere analysed here, six exhibited maximum flocculation at a size greater than 0.0055 mm. This supports the above conclusion that flocculation in the ooze is stronger than that in the gyttja (see above).

Out of the nine surface ooze samples from the three small lakes analysed, three exhibited maximum flocculation at a size greater than 0.0055 mm. This supports the above conclusion that ooze flocculation is generally stronger than in Windermere.

Organic Content

Pennington (1943, 1947a) claims that the ooze in Windermere, as well as the gyttja, contains an average of 20% of organic detritus. However, detailed variations were observed and may be significant.

Stratigraphic Variations. The representative data are listed in table 32a; Trip 5 ooze does not contain significantly more organic detritus than Trip 2 ooze ($P > 0.05$; fig. 77b). Trip 1 ooze is significantly higher in this

a. Miscellaneous Property Variations.

b. Mechanical Property Variations.

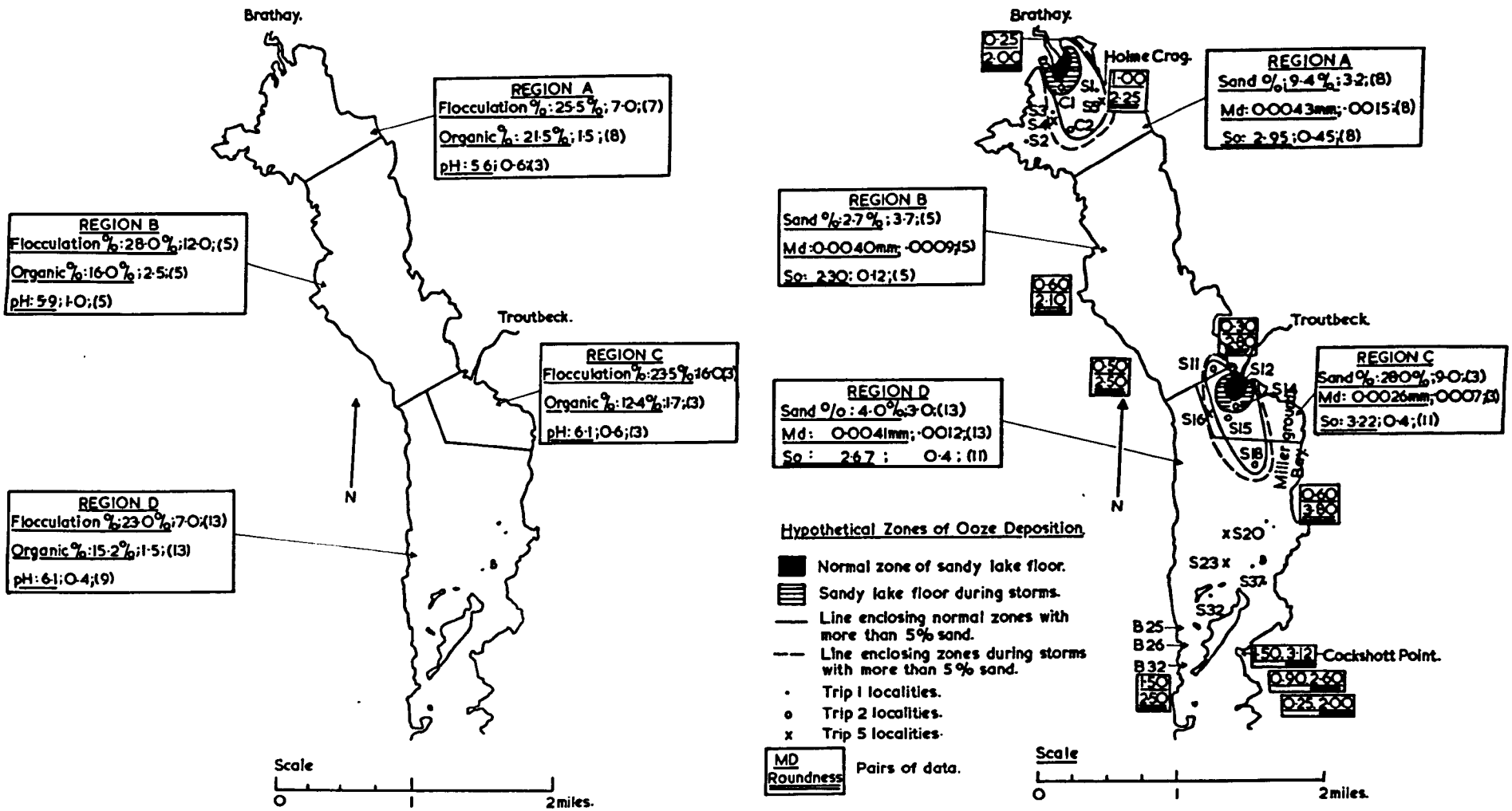


Figure 78. Property Variation Maps of the North Basin of Windermere: Representative Data for Ooze.

N.B. No distinctions are made for the different "facies" due to insufficient data.

Statistical comparisons in figure 77.

respect ($P < 0.05$; fig. 77c).

The organic content of the Windermere ooze samples counted together is significantly lower than the gyttja samples ($P < 0.025$; fig. 77d). Thus the trend first established in the gyttja whereby the organic content was decreasing in the upper layers (see above), appears to be continued at an increased rate into the ooze.

Geographical Variations. The representative data are shown in figure 78a; from these the organic content appears to decrease downstream. Thus, results from Regions A and B counted together were significantly higher than Regions C and D ($P < 0.025$; fig. 77e).

The three Windermere near shore silts are not listed; the organic matter here consists entirely of fine detritus (fig. 14b; Chapter 4), which has not been incorporated in the deposit by biological activity. Thus the organic content of these shallow water deposits varies entirely according to local conditions. The beach material was not examined for organic matter (fig. 14a).

Ooze from Grasmere and Rydal Water appears to contain a slightly higher proportion of organic matter than that from Windermere; while Elterwater ooze contains very much more (table 32).

Water Content

Unfortunately, due to the surface sampling procedure adopted here in which lake water was inevitably bottled with the sediment, it was not attempted to measure the water content of the ooze in this work.

pH

The significance of pH values in the general context of the environments in the basin is discussed more appropriately in Chapter 31. It may have changed since sampling (see above).

Stratigraphic Variations. The representative data are listed in table 32a; from these it appears that Trip 2 ooze was more acidic than Trip 5 ooze; this was not supported statistically.

The pH of all the ooze samples counted together is indistinguishable from the gyttja samples. Thus the ooze period of deposition appears to be maintaining the general level of acidity in the lake environment, so that no significant stratigraphic variations are noted throughout the entire Post Glacial period.

Geographical Variations. The representative data are shown in figure 78a; from these, it appears that there is a slight tendancy for increasing acidity downstream though this was not confirmed statistically. The three Windermere near shore silts were about the same as the ooze in this respect.

Ooze from Grasmere and Rydal Water appears to be considerably less acidic than that from Windermere, while Elterwater ooze is about the same (table 32).

Mechanical Distributions

The ooze facies had not attained mechanical stability (see above). See above for analytical limitations.

Particle Populations. The three Windermere ooze facies are considered separately from those in the three small

lakes. The near shore silts and beach deposits are also considered separately. The mineral content of the ooze is less constant than that of the stabilised gyttja (Chapter 31), but all these deposits are composed of basically similar Post Glacial "clay" and "silt" (redefined) fundamental popula-tions (see above). The clay fractions vary slightly in their degree of weathering.

The triangular diagram (fig. 62a) showed the major-ity of present day lake deposits to be in the still water grouping near the clay-silt edge of the triangle. The beach material with 100% sand and pebbles was not plotted. The exceptions were the three near shore silts and one sur-face ooze sample taken in April-May, 1961 from near Troutbeck mouth. These four were "fine sandy lake deposits" (Chapter 17) and were deposited in exceptionally active lakewater conditions.

Zones of Deposition. The general processes of deposition have already been considered (Chapter 20; also see above). The predominance of fine/flocculating chemically altered mineral "clay" material over coarser discretely settling unaltered "silt" material is the reason for the majority of surface ooze samples being classified as still water deposits. It is important to assess the actual positions of these zones of deposition (sketched hypothetic-ally in figure 67). In this respect the three Windermere ooze "facies" were considered separately:

a. In January, 1961 (Trip 1), only one of the three samples taken near Brathay mouth contained more than 5% sand; the locality of this sample (S1) suggested that one component of the river water was sweeping over towards Holme Crag on

the eastern side of the lake. None were taken at Troutbeck. Two from the threshold among the islands (at localities S32, S37) contained more than 5% sand.

b. In April-May, 1961 (Trip 2), both the samples taken near Brathay mouth contained more than 5% sand; locality C1 containing nearly twice as much as locality C2, as expected. These localities suggested that another component of the river water was sweeping straight out towards deeper water. Four samples taken near Troutbeck contained more than 5% sand. One (S11) was 400 yards (metres approximately) north of the inlet. Two were between 100 and 200 yards away and directly opposite the inlet; the nearer sample (at S14) was just beside S12 where the floor was too sandy to take samples; this contained more (35%) than the further sample at S15 (28%). One (S18) was about 800 yards south of the inlet in deep water. No samples were taken from the threshold.

c. In August, 1962, just after the flood maximum (Trip 5), both the samples from near Brathay mouth contained more than 5% sand and, again, the locality on the eastern side of the lake (S5) contained more (28%) than the locality slightly west of Brathay mouth (8% at S4). South of Holme Crag, on the eastern side of the lake, the sand proportion dropped to less than 5%. Off Troutbeck, there was a large area of the lake floor about 200 yards across, where samples had been taken during Trip 2 (for example, at S13) but which was now too sandy for material to be held in the F.B.A. Automatic Sampler (fig. 11). The nearest successfully sampled locality to Troutbeck mouth during these floods was S16, 300 to 400 yards away from the inlet, where there was 20% sand. Again

no samples were taken from the threshold though some of the material on the slope up to it from deeper water contained more than 5% sand (S20, 23), in contrast to the two previous occasions.

There are three further considerations with respect to this ooze "facies" taken just after the flooding maximum. The ooze/gyttja boundary was not absolutely sharp at those successfully sampled localities near to river mouths, as it had been on all previous occasions. The ooze itself at these same localities was homogeneous throughout instead of being in two portions (see above). At one locality (S16) there was a piece of fresh green moss found incorporated in the gyttja just below its gradual boundary with the ooze. All these three considerations suggest that, during the maximum of these floods (the worst known in the Lake District for some time), the river water currents in places on the lake floor were active to the extent of eroding and carrying off in suspension the entire depth of the surface ooze and the uppermost gyttja. During sampling, the floods had abated slightly and some of the localities were again in the zone of deposition so that the sampled material was <u>all</u> very recently deposited; thus, it was homogeneous down to the gradual ooze/gyttja boundary. It is for this reason that the surface sampled gyttja was not, in fact, used in the detailed examinations of variations within the major gyttja facies (see above). It was used however for studying the ooze/gyttja boundary in Trip 2 (see above).

These varying zones are summarised in figure 78b.

Grasmere and Rydal Water both showed this type of

zoning when sampled in August, 1962 (before the flooding), with a comparatively high proportion of sand near the river inlet decreasing towards the middles of the lakes. The material sampled near the outlets of both these lakes contained slightly more sand than those in the middle due to winnowing out of fine material. Elterwater, however, is at the junction of the rivers Brathay and Great Langdale Beck and it has recently been dredged. The conditions there cause the bottom sediments to be comparatively high in sand (> 10%) and this proportion increased downstream.

The sand grade percent of the Windermere surface ooze was studied for stratigraphic and geographic variations, regardless of the positions of the above zones. The Grade Mean was not examined as before.

Stratigraphical Variations. The representative data are listed in table 32b); from these it appears that Trip 1 ooze contained less sand than either Trip 2 ooze or Trip 5 ooze; statistical comparisons were not made, however, because the sampling during each Trip was not random with respect to the river mouths as has already been explained. However, a test was performed comparing all the Windermere ooze samples in this respect with all the gyttja samples; though it is not certain that the two groups of data were geographically equivalent to each other (fig. 19). It was confirmed that the ooze contains significantly more sand than the gyttja ($P < 0.005$; fig. 77b). This would be in broad agreement with the hypothesis that the main deltas have moved into the lake during the Post Glacial period and have brought higher proportions of sand material progressively further into

the deeper water. It may also suggest that the rivers have continued becoming more active during this period (see above).

Geographical Variations. The representative data are shown on figure 78b; from these it appears, as expected, that Region A ooze contains more sand than Region B, and that Region C contains more than Region D. Statistical tests were not performed, however, because the regions were heterogeneous and the semi interquartile ranges of all the sets of representative data, except Region C, were excessive in comparison with the corresponding median values. The reasons for this heterogeneity are seen on figure 78b; this indicates that these arbitrary Regions were not entirely satisfactory with regard to all the sedimentary properties. In practice, however, they were generally found to be useful.

Variations in the Mechanical Properties of Prosent Day Deposits

Windermere Surface Ooze

Having established the zones of deposition and the varying proportions of sand in the ooze, the stratigraphic and geographical variations of the mechanical properties of the ooze are examined. Again unfortunately, the relationship of the coarser discrete distribution to the true settling distribution is not fully understood (see above). Geographically there appears to be a tendancy for the particle size to become slightly coarser further away from river mouths. This reversal is not supported statistically and the representative data are inadequate; it is discussed in Chapter 23. Stratigraphically sand from Trip 2 ooze appeared to be coarser (0.140 mm;0.23;(6)) than the other two (Trip 1: 0.116 mm;-;(2); Trip 5: 0.100 mm;0.007;(4)).

Small variations in the other three properties were not under--stood. Sk is always positive as expected (Chapter 20).

Fine Fraction.

The representative data for all the main Windermere Post Glacial deposits are given and discussed above. Represent--ative curves for surface ooze are illustrated with a skewness of 1.00 and a kurtosis of 0.28. Md and So are studied in more detail.

Median Diameter.

This represents the discrete coarseness of the fine mat--erial just prior to deposition (Chapter 20). MD remains compar--atively constant so that Md/MD is not measured here.

Stratigraphic Variations. The representative data are listed in table 32b; from these it appears that Trip 2 ooze is considerably finer than both Trips 5 and 1. Both these relation--ships are confirmed statistically ($P < 0.005$; $P < 0.005$; fig. 77 g and h respectively).

Geographical Variations. The representative data are shown in figure 78b; from these it appears that coarseness dec--reases downstream from Brathay though this is not confirmed statistically.

Sorting. ("Dispersion")

Stratigraphic Variations. The representative data are listed in table 32b; from these it appears that So values are high--er in Trip 2 ooze than in both Trips 5 and 1. Statistical comp--arison confirms this relationship between Trip 2 and Trip 1 ($P < 0.05$; fig. 77i) but not between Trips 2 and 5.

Geographical Variations. The representative data are

shown in figure 78b; from these it appears that sorting improves downstream and that, thus, flocculation is more intense close to inlets. None of these relationships are confirmed statistically (also see above).

Surface Ooze from the Three Small Lakes. (table 32b)

In Elterwater, the only one of these three where three coarse fractions are available for comparison, the relationship of MD becoming coarser downstream is again apparent. In Grasmere and Rydal Water Md appears to be about the same as in Windermere. In both these lakes Md is coarsest near the inlet, though in Elt--erwater it is about the same at all three points. So values are about the same in Elterwater as in Windermere (table 32) but it is lower in Rydal Water and higher in Grasmere. The relation--ships between So, flocculation, and the positions of the river inlets are not clear due to inadequate data.

Two representative curves are illustrated for the ooze facies; these are from Windermere (fig. 79). They are of Trip 1 ooze (a) and Trip 2 ooze (b). The latter contains slightly more sand and is finer and poorer sorted.

Windermere Near Shore Silts.

A representative curve (sample no. 41) is illustrated here in figure 79c. The "sandy" portion appears to be a slightly finer form of the sand in normal Post Glacial lake deposits. The fairly strong negative skewness (Sk = 0.45) is probably due to the appearance of fine "admixtures" during the comparatively calm period prior to sampling. These may be swept away when aqueous activity increases for any reason. It is thought that this near shore silt facies represents the shallow water form of the

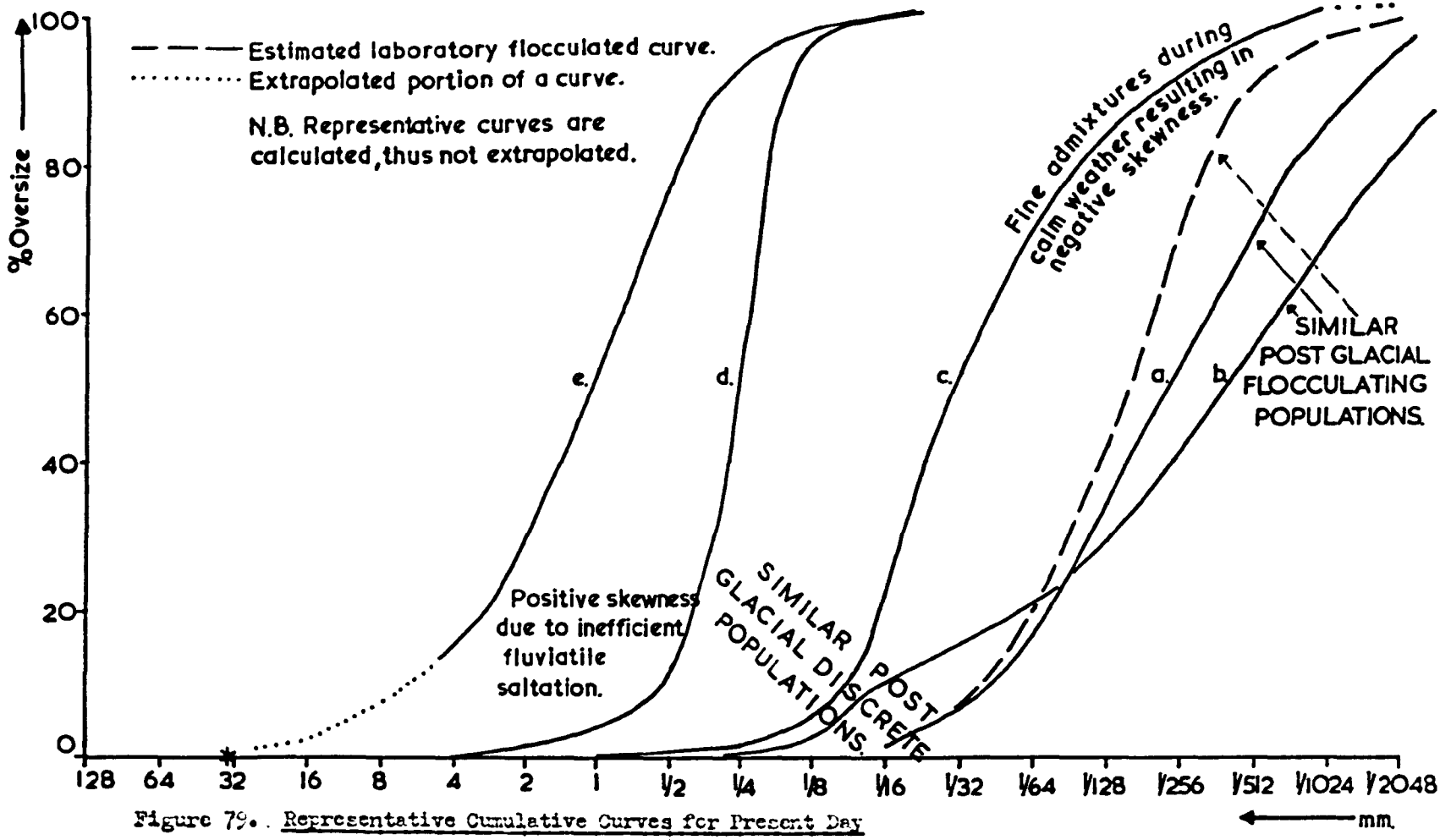


Figure 79. Representative Cumulative Curves for Present Day Lake Sediments. (N.B. Size scale is compressed so that half the angle of slope is equivalent to the same sorting value as in figure 51a)

surface ooze and gyttja. The settling distribution is unimodal, thus the size distribution is likewise because it was too coarse for flocculation, otherwise the principles of its deposition are similar. The mineral particles of which it is made up are simil--ar though the predominance of "silt" discrete particles over "clay" flocculating ones is an expected reversal of the deep wat--er situation. Also calcite is again removed by normal Post Glacial lakewater corrosion. The organic matter in near shore silt is in the form of discrete vegetable particles and thus their proportion is very variable. In deeper water this detritus is incorporated by biological activity into the deposit and it is not so variable.

The thin shallow water ooze and gyttja are more similar to deep water forms than to near shore silt; except that they con--tain a fairly high proportion of sand.

Beach Deposits. (Mechanical and roundness analyses)

These were sampled from "shoestring deposits" nearest to the water's edge (Chapter 4; fig. 14b). They were not studied in detail so two representative curves (samples nos. 48, 57) are ill--ustrated here in figure 79 d and e respectively. The median diameter varies as does the sorting, though the majority of these samples had SO values of less than 2.00. Skewness is significant--ly positive; this was tested by the $n^{\frac{1}{2}}$ test (Chapter 18) using 1.00 as the standard median value for Sk. It is in general agree--ment with Friedman (1961) who claims that this positive skewness is due to the less efficient transport of coarse particles by saltation than of fine particles by suspension.

Approximate geographic variations of roundness and MD are shown in figure 78b; from these it appears that roundness,

particularly, as well as the coarseness of these particles at the water's edge tends to be more pronounced on those beaches which are more exposed to the prevailing wind direction "funnell--ing" along the length of the lake due to the high ground on either side. On Cockshott Point there is a sandy spit hooked around towards the north suggesting that the more effective wind direc--tion is from the south. This makes the beaches on the eastern side of the lake more exposed than those on the west (fig. 78b). Thus the sand exposed on these Cockshott Point beaches, and in Millerground Bay and at Holme Crag, is generally more rounded and coarser than those on more sheltered beaches nearby (for example, south of Cockshott Point) and those on the west side of the lake. Variations of sorting, skewness, and kurtosis were random and are not examined.

At the localities where both beach material and the underlying drift were sampled (B4, B9, B16, and B37), as expect--ed, the beach material was more rounded than the pebbles (Chap--ter 21) incorporated in the drift. A more general comparison between the roundness of all drift samples and beach material (2.55;0.28;(22)) shows that these later deposits, which have been exposed to more intense abrasion for a longer period, are signif--icantly more rounded than the pebbles from which they were in part derived. ($P < 0.05$; fig. 77j).

At these same localities median diameter relationships vary. Sorting is better in the beach material as expected. This is confirmed by a general comparison between the sorting of all the drift samples (see Chapter 21 ; also fig. 61) and the beach material (1.32;0.15;(23)); ($P < 0.005$; fig. 77k). Skewness is more consistently positive in beach material ;the relationship between the respective kurtoses is obscure.

Chapter 23. Summary of Late Quaternary Sedimentation in the North Basin of Windermere.

Relationships between Physical and Miscellaneous Properties.

Many of these were plotted on two-dimensional scatter diagrams to discover relationships existing between them. None of these scatters gave simple relationships; but there are a few worthy of note.

Water Depth and Sediment Coarseness. No relationships were found between sand grade percent, Md, MD, grade mean (all measures of coarseness) and present day water depth. This is in contrast with Eakin (1936; also see Chapter 20) who claims that sediments of this nature accumulate thickest in the deepest part of the lake due to gravity. Also, Kofoed and Gorsline (1963) say that bottom topography is the controlling factor in sedim-entation, dissipating wave and current energy and channelling sediments to their place of deposition. However in Windermere, both the thickest and the coarsest deposits are near the two main river mouths, even in deep water. This confirms that the first important factor of Windermere sedimentation is the loss of impetus of river water as it enters the lake. Generally, coarse material occurs at any depth according to conditions, whereas fine material is restricted to deep water and sheltered areas (Hough, 1942).

Mechanical Distribution Properties. As expected Md and grade mean are closely related. Md, So, Sk, k are statistically independant (Pettijohn, 1957). Thus they are plotted for relat-ionships resulting from deposition in Windermere. Hough (loc. cit.) showed that sorting and skewness of sandy sediments are

related to their coarseness; the flocculating fraction in Windermere, however, obscures any such relationship. In this respect, Griffiths (1951) recognised that poor size sorting is found in fine sediments (as in this work where SO is generally lower than So) and said that this is often due to flocculation. Hough also showed that well sorted sediments have approximately symmetrical size distributions but that poorly sorted sediments generally have strong negative skewness. The present results are in broad agreement with this, particularly where colloidal particles in the poorly sorted flocculating fraction caused strong negative skewness (see above). Inman (1949) has suggested that these relationships between size statistical attributes are due to the fluid mechanics of deposition. There appeared to be a trend in Windermere whereby SO increases with MD in organic lake sediments; there were too few observations, however, to provide significant results. The relationships of kurtosis to the other properties are not understood except that it is high in the polymodal boulder clays as expected.

Roundness is often related to coarseness in beach deposits (Hough, 1942). However (as with Hough's material) there was found to be no relationship in Windermere (fig. 78b).

Flocculation. There are no observable relationships between the flocculation and the size distribution of fine material. This supports the postulated complexities of the effect of flocculation. It does not support, however, a simple improvement of size sorting with low flocculation. There are relationships whereby maximum flocculation occurs at coarse size grades only in sediments both relatively coarse and well sorted. It occurs at fine size grades in a wider variety of types.

These support the partial control of this property by grain size distribution (Chapter 22) but its significance remains obscure. Maximum flocculation and the size at which it occurs do not appear to be related. Flocculation is not dependant directly on pH ("salinity", Sherman, 1953); nor does it cause observed changes in water content ("porosity", loc. cit.).

Other Miscellaneous Properties. The coarseness though not the sorting of the fine material in Windermere affects its porosity so that the water content is small where Md is large. In this respect there are two groupings on the scatter diagram (fig. 80a); though neither trend was proved to be significant. This displacement of organic lake sample points and clayey drift sample points is caused by the incorporation of organic matter as an integral part of the ooze and gyttja. It was thus expect--ed that the proportion of organic matter should affect porosity Again the same two groupings are observed here, each showing that water content increases significantly with organic matter ($P < 0.05$ for both groupings; fig. 80b).

An important scatter diagram is that on which Md incr--eases significantly with organic content ($P < 0.005$ for the org--anic lake sediments; fig. 80c). This indicates that organic matter is a second important controlling factor in the sediment--ation of flocculating material in Windermere. The sand prop--ortion and MD, however, both representing the discrete popul--ation, are independant of organic content.

The projected "three-dimensional" scatter diagrams were drawn to bring out relationships between flocculation, Md, and water content, thus demonstrating that porosity is after all dependant on flocculation to some traceable extent; and between

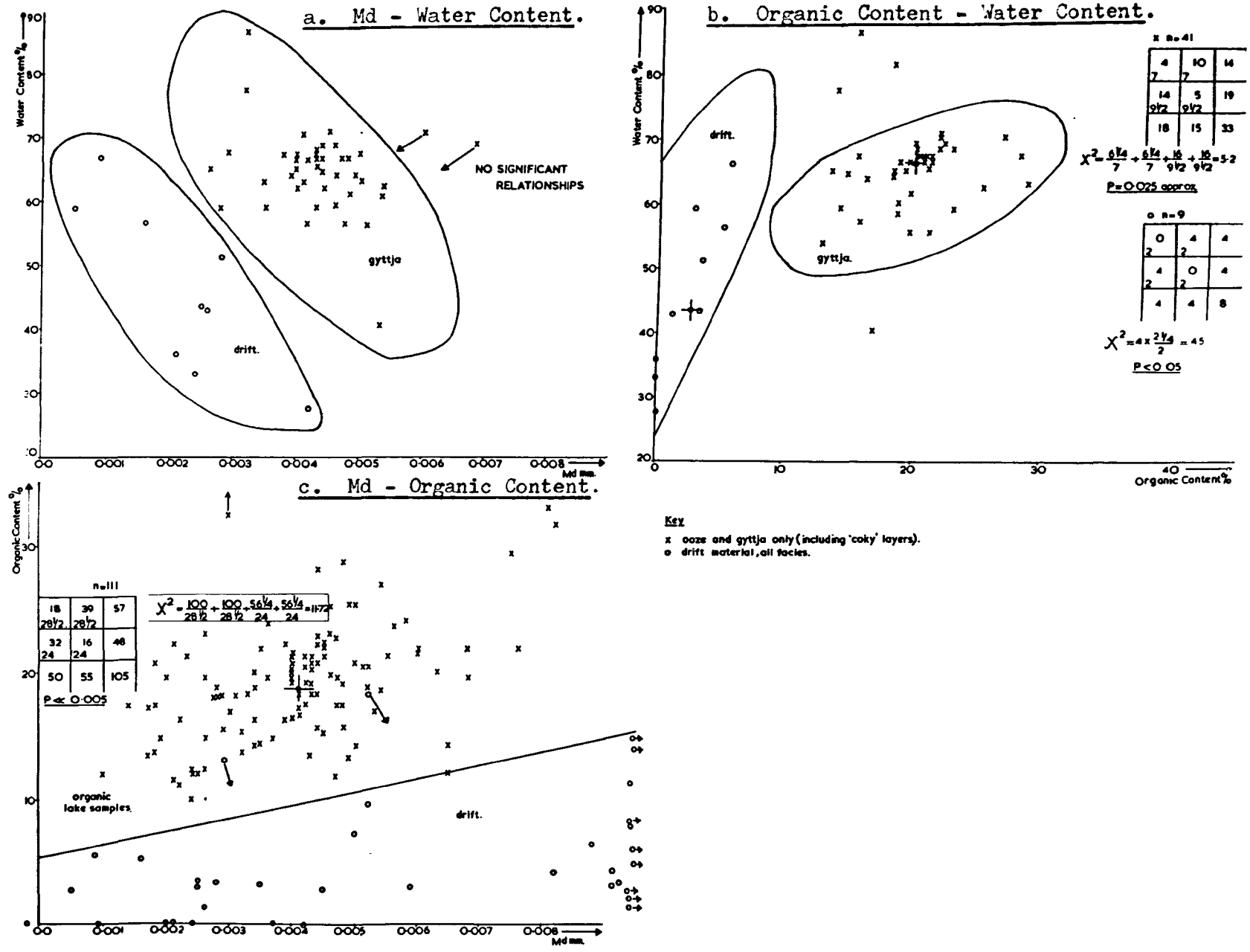


Figure 80. Miscellaneous and Physical Relationships; Chi Square Probability Tests; also Groupings showing displacement of drift and Post Glacial lake material.

flocculation, Md, and organic content, thus demonstrating that flocculation is after all dependant on organic content. Flocc--ulation was the third "projected" axis in each case but failed to produce significant scatters.

Summary of Lake Deposition.

The stratigraphic and geographical property variat--ions in Windermere sediments have been outlined. These are shown in tables 28, 30, 32, and figures 71, 75, 78 (Chapters 21 and 22). Block and cross-sectional property variation diagrams were drawn but are not presented here. Relationships between properties have been discussed above. These are all geological responses to local genetic and environmental conditions of comp--osition, erosion, transport, and burial. This summary is a general interpretation of these responses.

a. Sediment composition is discussed in Part IV; but the relevant conclusions are referred to here.

b. Erosion and transport were not studied directly; there always tends to be a natural balance between the potential for erosion, largely dependant on climate, and the resistance to erosion offered by the terrain, largely dependant upon drainage area, soil cover, land use and vegetable cover (thus climate), and human factors. Thus the quantity and composition of trans--porting stream loads vary with these evolving factors.

c. Deposition and burial, the chief objects of this study, are summarised below with regard to the special conditions in Windermere. The nature of lake deposition is dependant, in part, on its shape, surface area, and depth.

Not all these conclusions have statistical confirmation. Detailed results may be checked in Chapters 21

Two basic controls have emerged from the earlier sect-
-ions of Part III:

a. Physical controls. Loss of impetus of river water entering the lake and resulting flocculation and deposition of fine material.

b. Chemical controls. The incorporation of organic matter as an integral part of the Post Glacial lake sediments. This is due to biological (bacterial) activity on the lake floor, and is thus related to the phenomenon of summer stratification of lake-
-water (Chapter 2).

This summary applies these two principles to the diff-
-erent stages of Late Quaternary sedimentation in Windermere.

Late Glacial.

After sufficient ice had melted and sedimentation had started in Windermere, the deposits took the form of normal Late Glacial laminations or summer/winter varves. Occasional fast moving bottom currents resulted in localised beds of coars-
-er graded material. These sediments accumulated rapidly due to intense erosion of the bare terrain, and there was spasmodic slumping on the steeper parts of the lake floor. The absence of vegetable detritus indicates a cold climate; but the steadily decreasing size of rafted pebbles in the deposits suggests an amelioration in this respect. Increasing grain size of the finest pink clay material suggests increasing lakewater mobility.

There were three mineralogical types of sedimentary material:

a. Pink "clay". Very fine, not entirely smaller than 0.002 mm. Calcite free non hydrated alteration products.

b. Dark grey "silt". Moderately fine

less than 0.064 mm and less than 0.002 mm. Calcite bearing non hydrated mainly disintegration products.

c. Light grey "sand". Coarse silt and fine sand grades. Calcite bearing non hydrated mainly disintegration products.

There was no flocculation so deposition was of graded mixtures of these three types in different proportions. The finest fractions largely consist of a. They are thus pink and plastic textured, well sorted, and their size distributions are approximately symmetrical. The normal coarser fractions largely consist of b. They are thus dark grey; there are, however, "admixtures" of a causing both the semi plastic texture and varying degrees of poor sorting and negative skewness. The abnormal coarsest fractions largely consist of c. They are thus light grey and friable; there are, however, admixtures of a and b causing negative skewness and, sometimes, bimodality. Thus these three facies merge into one another.

Post Glacial.

This was marked by an influx of organic detritus in response to the amelioration of the climate and the consequent appearance of vegetation. A new erosional balance was set up and Pennington (1943) suggests that there was a corresponding decrease in the quantity of mineral matter entering the lake. These responses are marked in the gyttja sequence by the following changes from the earlier graded facies:

a. Incorporation of the organic detritus as an integral part of the reddish muddy sediments. This suggests biological, probably bacterial, activity on the lake floor.

b. Sharp increase in water content to a new high homogeneous level throughout; lack of compaction; lack of grading or

marked stratification. These suggest flocculation and a result--ing fundamental change in sedimentation.

c. Sharp increase in general coarseness; the gyttja is approximately the same as the earlier dark grey silt and is therefore significantly coarser than the predominant pure pink clays. This suggests the changed erosional balance and sediment--ation processes.

The bulk of solid material was brought into the lake as concentrated river suspension loads during storms (solubles were continually being transported). The swollen rivers lost much of their impetus on meeting the still lake water so pebbles and coarse sand were sorted out of the load at the deltas. Dense sediment laden currents underflowed the clear lakewater as they spread outwards from here. Near the deltas they scoured the uppermost layers of previously deposited material from comparat--ively narrow zones of the lake floor and left only sand. Furt--her out flocculation overcame mechanical dispersal and fine material was deposited. After the storms had abated, flocculat--ed fine material moved into the earlier zones of sand deposit--ion and equilibrium was reestablished throughout the lake with the newly acquired load of sedimentary material. The deposits near river mouths are more varied than those in less disturbed deeper water, and they are not stratified at all.

There were two basic types of sedimentary material, thoroughly mixed together in the deposits due to flocculation, porosity, and reworking by organisms.

a. "Clay". Hydrated, strongly altered from the parent rocks, fairly fine grained (0.020 mm in contrast to its Late Glacial equivalent), and flocculating.

b. "Silt". Non hydrated, altered slightly (absence of calcite) from parent rocks, from very fine upwards, non flocc--ulating.

The thin layers of pure mineral sediment were brought in during the earliest Post Glacial period (transitional series) as a result of landslides or equivalent catastrophic occurences ("finest boulder clay fractions", Pennington, 1943). They were generally local in extent though they culminated in the widespr--ead "top clay band". They were non hydrated, non flocculating, they contained calcite, and were very similar to the equivalent Late Glacial material (see above; also see Chapter 30). This demonstrates the importance of organic matter in causing alter--ation of the minerals during the Post Glacial period.

Stratigraphically, the organic content and the coarse--ness of the gyttja reached a maximum about half way between the top clay band and the ooze (3500 to 4000 years ago). It is thought that this represents a slow, minor, climatic change, and the resulting gradual evolution and reversal of the erosional balance, due to the vegetable cover (Brown, 1951, p.399; Gillully et al, 1958, p.72). The acidity does not change sign--ificantly but flocculation has been increasing gradually since the first influx of organic matter. Correspondingly size sorting which was relatively good at first became poorer in the younger deposits. Thus, in spite of bacterial disintegration, the pot--ential for flocculation is preserved in the gyttja, to some extent, to the present. Post Glacial sorting processes cannot be related strictly to those in the Late Glacial due to this flocculation factor; however it is seen that the graded pink clays are better sorted (size) than the gyttja, though the dark

b. Silt : Non hydrated, altered slightly (absence of calcite) from parent rocks, from very fine upwards, non floccu-ulating.

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grey silts are poorer sorted.

The sandy zones of deposition near rivers moved further into the lake as the deltas were built out. There is also an increase in the proportion and coarseness of the sand content of the younger sediments. Thus, there may have been a general in--crease of lakewater mobility throughout the Post Glacial period.

The black colouration and the occasional coky fragments in the widespread layer 50 cms from the top of the gyttja are thought to have been brought in as windborn ashes from local forest fires possibly started by early man. The sedimentary properties are otherwise the same as the gyttja though the conc--entration of carbon ash caused a low weight loss on ignition result (N.B. Fine fraction only).

Surface Ooze.

This is a blackish layer normally overlying the gyttja with a sharp boundary. It has similar depositional properties and is composed of the same two basic mineralogical types mixed homogeneously without stratification. The change from gyttja to ooze was a response to the extensive human settle--ment in the area. Thus, while natural afforestation reduced the potentially strong erosion in gyttja times, its replacement by widespread agricultural cultivation in the last 200 years allowed accelerated erosion and a new erosional balance has been attained. At the same time, while vegetable detritus and its decomposition products were important in gyttja sedimentation, its partial replacement by sewage pollution has caused a new chemical balance to be attained. The geological responses to these changes are seen in the surface ooze:

a. Organic detritus content decreased sharply in the ooze. This continues an earlier trend (see above) but the sudden drop was due to the artificial removal of forests. However, the com--bined effect of pollution and vegetable decomposition products remained highly effective towards causing the alteration of clay minerals and flocculation (see below).

b. Colour change from reddish to blackish mud. This was caused by the new environment which is strongly reducing due to increased biological activity, and removal of oxygen, in the hypo--limnion during the summer months. The sudden predominance of the large diatom Asterionella is a reflection of this increase.

c. Flocculation increased sharply, clay minerals tended to be more hydrated in the ooze. This indicates that sewage poll--ution was more intensely effective than earlier vegetable decomp--osition products. Increased flocculation has resulted in a higher water content and a total absence of stratification.

N.B. pH remained at a constant level of acidity through--out the Post Glacial period (see above).

The upper portion of this ooze layer is unstable so there is no evidence as to changed mechanical distributions (see below). The sandy zones near the river mouths, however have continued to move out. General lakewater mobility (equivalent to sand proportion and MD) has continued to increase.

So long as conditions remain as they are, with human factors and organic detritus controlling sedimentation, the surface layer of sediments will undoubtedly continue as at pres--ent. The question remains as to whether this, when buried, will retain its distinctive characteristics, noteably its colour or whether it is destined to become incorporated in, and indist-

-inguishable from, the earlier reddish Post Glacial muds. Pennington (1943, 1947a) suggests that it is, and will remain, stratigraphically distinctive. Murray (1956; also see Chapter 2), working on a similar sequence of sediments in Lake Mendota, comes to the same conclusion. The alternative is based on the fact that there is enormous reworking by macro and micro biol--ogical activity in the upper layers of lake sediments (Twenhof--el and McKelvey, 1941). Thus the black colouration in the red--ucing environment may be ephemeral. If this is the case, as the sediments are buried deeper and the zone of biological activity moves up, the reducing environment and the resulting black col--ouration would slowly be oxidised and become reddish. None of the changes mentioned above are conclusive for one alternative or the other. Thus from a purely analytical viewpoint, ooze and gyttja may be similar deposits preserved under different redox conditions according to depth of burial; or they may be diff--erent types of material. The only evidence found in this work that may be conclusive is that there is, in normal calm condit--ions, a compacted lower stable dark grey form of the surface ooze in deep water localities. This was probably the "final" form of the ooze so that it is, in fact, a permanently distinct--ive deposit. Thus, if, for example, humans left the area, their present settlement there would be recorded by a thin black layer in the reddish gyttja sequence.

There were further variations within this general frame--work. The ooze collected in April - May 1960 (Trip 2) contain--ed less organic matter and its grain size was finer than that collected in both January 1960 and also after the floods in August 1962 (Trips 1 and 5 respectively). Flocculation, however,

was stronger and, correspondingly, size sorting poorer in Trip 2. Also the clay minerals are less hydrated in the Trip 2 ooze than in the others (Chapter 30).

These variations in Windermere ooze are comparable to the variations between ooze "facies" from all four lakes exam--ined (Windermere and the three small lakes - Chapter 22). It is clear that the material at the sediment/water interface is highly susceptible to changing local and climatic conditions. The buried stable material is more mechanically and mineralogic--ally homogeneous due to reworking by organisms and to compact--ion. The differences between Windermere ooze "facies" and the three small lakes are accentuated by differences in surface area shape and depth.

Geographical variations in the Late Quaternary are rel--ated mainly to river mouths and to the lake shoreline. Thus organic content and acidity (gyttja only), grain size, proport--ion of sand, and flocculation (correspondingly size sorting improves) all decrease downstream from Brathay and Troutbeck. The coarseness of the sand group, however, appears to increase downstream. This reversal has on no occasion been proved, and indeed it is a reversal of the conclusions from the preliminary results (Chapter 8 and Appendix No. 3), though it is often obs--erved that increasing Md is accompanied by decreasing MD and vice versa. If this is so, the process is related to the strong--er flocculation near river mouths where the finer sand is drag--ged down to the lake floor with the large upstream floccules. This leaves coarser sand free to be carried further out. The locations of the zones of deposition were assessed from a field study and have been summarised in figure 78b. These are super-

-imposed on the general Late Quaternary trend for the deltas and zones to move further out into the lake, summarised in fig--ure 75b.

The relative importance of Brathay and Troutbeck rivers appears to have alternated in the Late Quaternary. Early on, during the formation of the glaciolacustrine "deltaic" clays and then of the "deltaic" silts, Troutbeck produced coarser sediments (fig. 62a, Chapter 17; and Chapter 21). During gyttja deposit--ion, Brathay produced the higher sand proportion further out in the lake (fig. 75b; Chapter 22). At present, Troutbeck has this wider zone of sand deposition (fig. 78b; Chapter 22). This alt--ernation is thought to be due to two factors:

a. The longer flood plain coarses of the rivers flowing in--to the lake at Brathay. These include several small lakes as sediment traps.

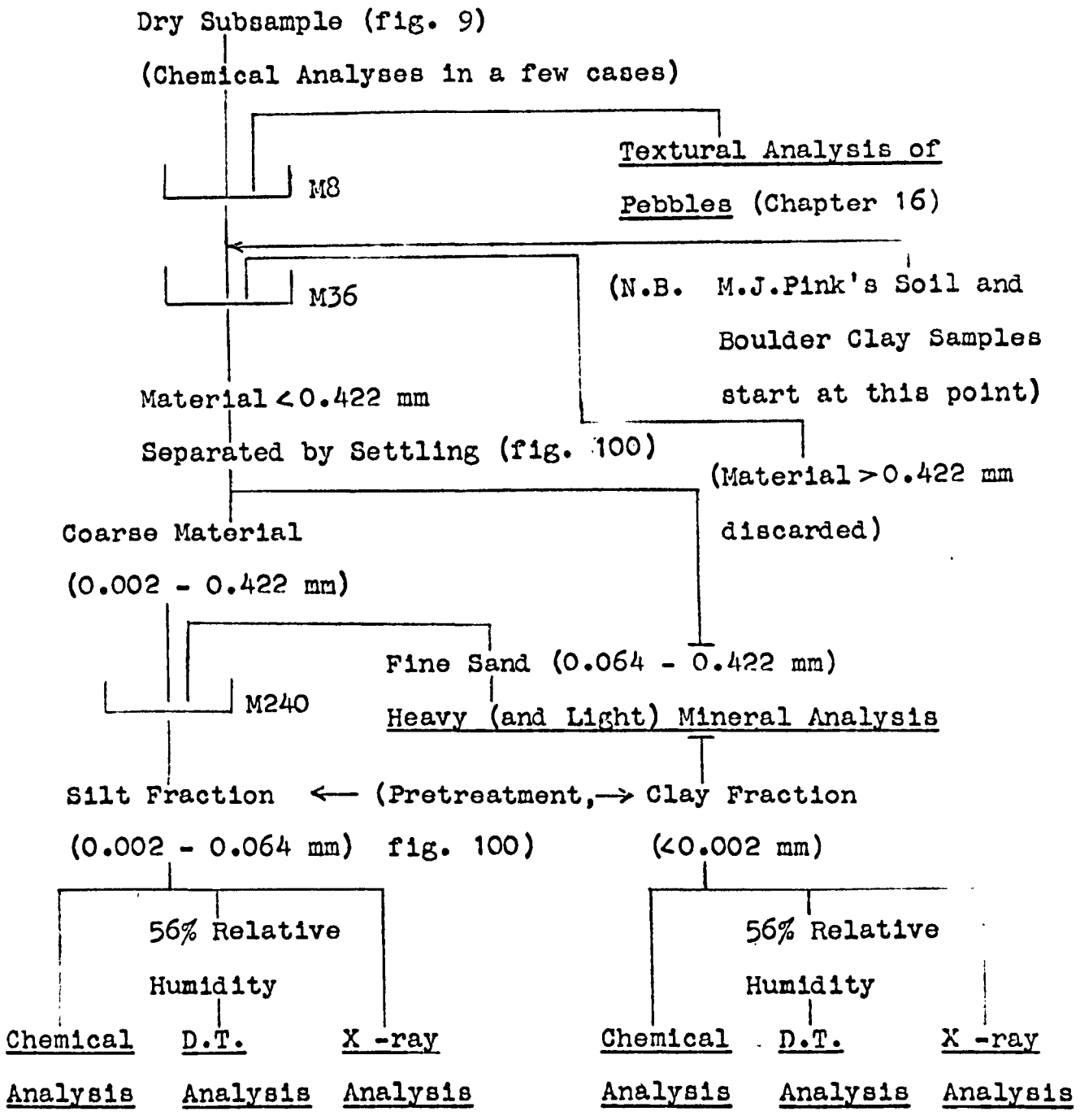
b. The basically more active Brathay, however, will have built out its delta shelf more quickly than the smaller inlet at Troutbeck. This shelf would dissipate river water energy and off shore sediments remain fairly fine.

Near Shore Silt and Beach Deposits.

Sheltered shallow water deposits are apparently ident--ical to the deep water ooze and gyttja with organic detritus incorporated, though the sand proportion tends to be higher due to winnowing out of fine material by wave activity. Organic matter has not been incorporated into the near shore silt and the beach deposits, however; the former are variable and negat--ively skewed due to calm fine admixtures; the latter are posit--ively skewed due to inefficient fluviatile saltation. They are coarser and more rounded on exposed beaches; also than drift pebbles

PART IV. QUALITATIVE ANALYSES.

(N.B. Figure 81 shows the Flow Sheet for all the qualitative analyses, the details are discussed in the appropriate chapters. All the Windermere samples analysed are listed in table 35 found below with Chapter 26)



(N.B. Rock Samples are crushed, then pulverised for 90 minutes before being brought to 56% Relative Humidity for D.T. Analysis; and prepared for X -ray Analysis)

Figure 81. Flow Sheet for Qualitative (and Textural) Analyses.

Chapter 24. Differential Thermal Apparatus.

(Mackenzie, Ed., 1957)

Principles.

This method is used for mineral studies of fine powders. A tube furnace is heated at a controlled rate from 0° to 1100°C. A sample block inside the tube typically consists of two small symmetrically placed crucibles, one containing a thermally inert powder and the other the sample to be analysed which is probably thermally active over the range. Thermocouples are connected to galvanometer recorders and inserted into the crucibles. Continuous curves are traced on two instruments:

a. The sample temperature.

b. The temperature difference between sample and inert.

The mineral content may be determined by comparing this temperature difference curve with standard curves of known minerals and mixtures of minerals. A difference curve generally represents a series of thermal reactions in the sample, exothermic or endothermic, caused by one of the following effects:

a. Release of molecular water.

b. Ignition of organic matter.

c. Release of hydroxyl groups.

d. Crystal inversion.

e. Recrystallisation.

f. Decomposition.

These reactions are generally recorded as peaks, sometimes succeeded by a shift in the base line. A specific reaction in a given mineral occurs over a comparatively narrow temperature range in most specimens containing that mineral and identification depends on this factor.

It was not possible until recently to purchase a complete D.T. apparatus and that used in this work is made up from several basic components with certain modifications and refinements.

Purpose of D.T. Studies.

The Windermere sediments contain a high proportion of fine grained material. The samples were analysed in the D.T. apparatus and the results compared with one another, with standard mineral curves, and with curves obtained by other authors. An important consideration in making up an apparatus for studying these sediments was the high proportion of organic matter in the Post Glacial lake material. This is ignited in an oxygen atmosphere giving an exothermic effect between 300°C and 500°C which tends to mask other peaks in the same range and otherwise to alter the curves. The introduction of an inert nitrogen furnace atmosphere was the simplest method for over--coming this problem; no other special refinements were necess--ary. A D.T. apparatus of this general nature, with controlled furnace atmosphere conditions (air or oxygen if required) will have wide applications for mineral investigations of fine grained sediments.

Apparatus.

N.B. All diagrams of D.T. curves reproduced in this section have endothermic effects to the right; the scale is in minutes for convenience. The conventional practice is used in subsequent Chapters.

The Original Apparatus.

This has been described by Hillier (1955). The Kent

Multelec Recorders were used in making up the new apparatus.

The Furnace. (fig. 82)

The Catterson-Smith furnace did not have a double ended core and so it could not be used satisfactorily for controlled atmospheres. A Gallenkamp's tube D.T. furnace (Cat. No FS 700) was used in conjunction with a high temperature silica tube.

The Furnace Windings and Control of the Heating Rate.

Ideally the control is such that the block inside the furnace is heated at a rate of 10°C/minute and this is exactly reproducible (Mackenzie and Mitchell, 1957). Thus a method for controlling the furnace windings was incorporated. This control is gained by setting a mechanical device to drive a pointer up the temperature scale of the controlling instrument at the required rate for the furnace windings. This programme is obtained by setting an electric motor to rotate an appropriately shaped metal cam very slowly. A swinging arm is spring held very tightly against the edge of this cam and is connected through a series of gears to drive the red control pointer up the scale at a rate dictated by the shape of the cam and the speed of the motor. This independant mechanical system controls the heating rate of the windings (fig. 83).

The temperature of the windings is measured by a furnace thermocouple appropriately placed. Rising temperature causes a galvanometer needle to move up the same scale simultaneously. Automatic control of the heating rate is obtained by a device which compares the actual temperature of the windings with that set by the control throughout a cycle, so that the power is reduced when the furnace is hotter than it should be at any stage

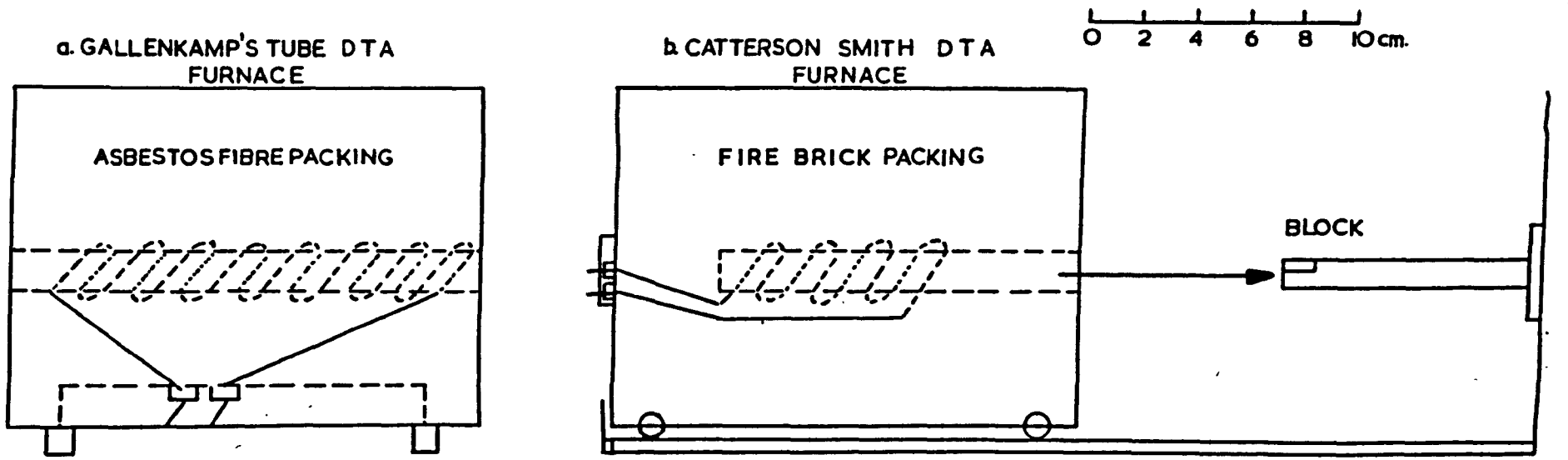


Figure 82. The Differential Thermal Furnaces.

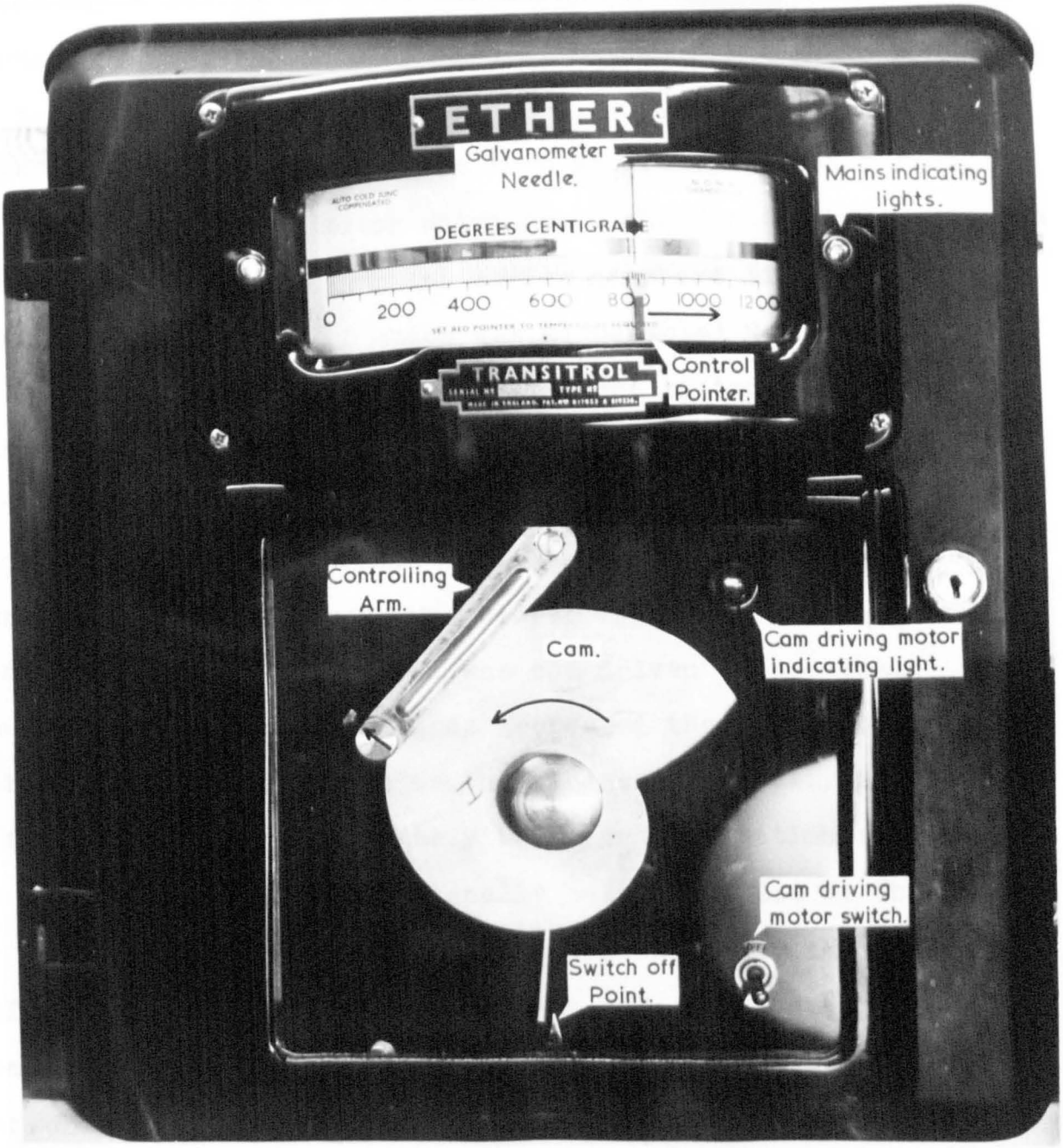


Figure 83 . Heating Rate Controlling Mechanisms.

and vice versa.

The original apparatus incorporated a Kent's controlling system which was in the same instrument as, and used the same thermocouple as, the sample temperature recorder. In this system the mains power to the furnace passed through a Variac auto-transformer and the supply from this was increased by a small reversible Drayton RQ motor which drove the Variac shaft. If the furnace was too hot a regular series of short impulses (the duration and interval of which was adjustable) were recieved by the motor from the controlling instrument to turn the Variac shaft and reduce the output. These impulses were automatically reversed in the controller when the furnace temperature dropped below that set by the control and the Variac output was then increased. An ideal cycle was started with the two pointers at room temperature; the control was cam driven up the scale immediately and so the impulses increased the Variac output. If the initial voltage set on the Variac was exactly correct and if the impulses were of exactly the correct duration and interval, the furnace was always fractionally below that set by the control and the Variac output was increased appropriately throughout a cycle. The major difficulty was that once this ideal had been departed from to the smallest extent the control was completely lost. Thus an erroneous Variac setting initiated effects that the system didn't react fast enough to control (fig. 84).

Besides this difficulty the silica tube and the metal sheath in the new tube furnace cause a temperature lag between the windings and the block which is considerably larger than that in the original apparatus. Thus it is no longer possible to use the same instrument and thermocouple both for controlling and for

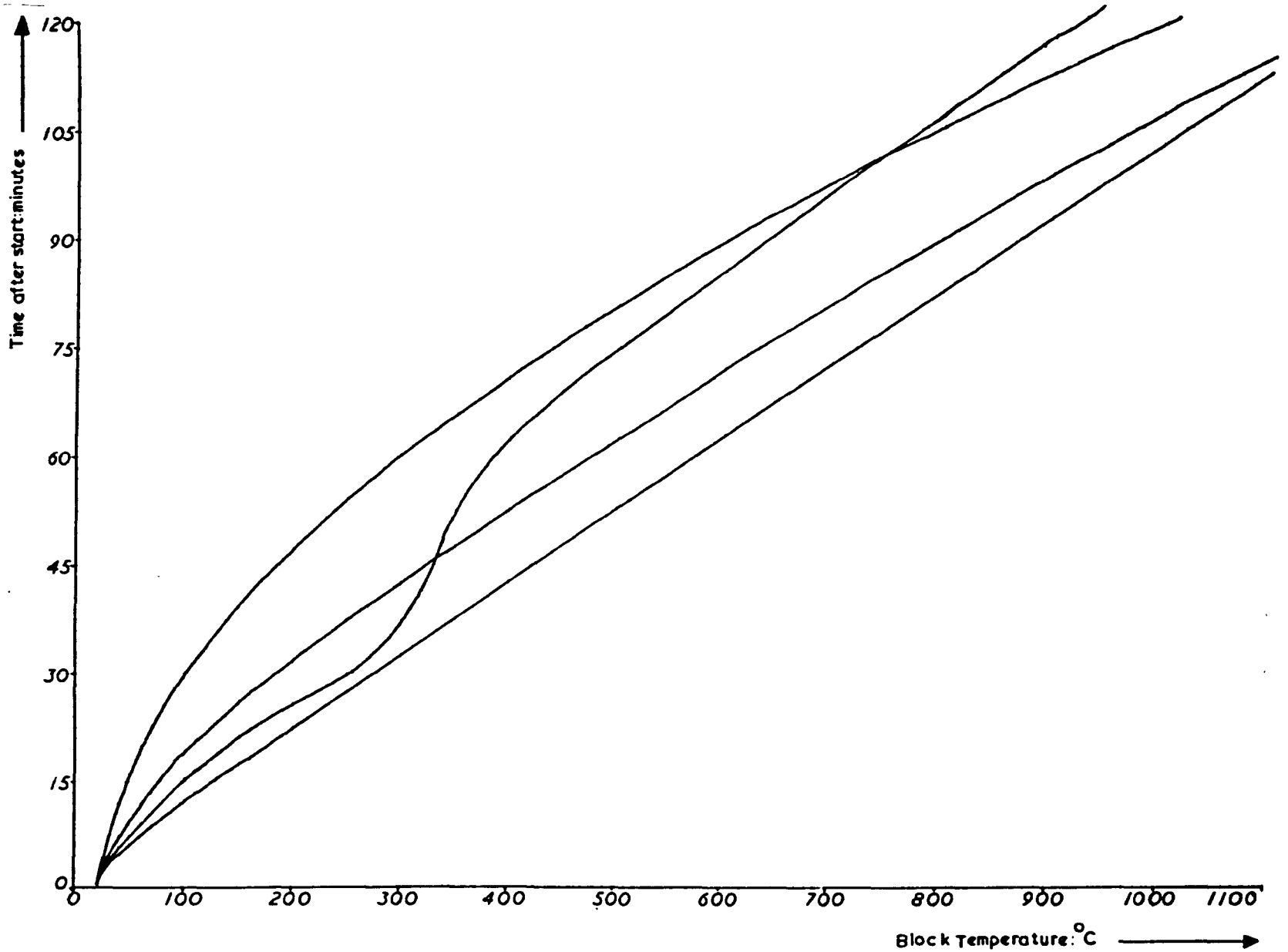
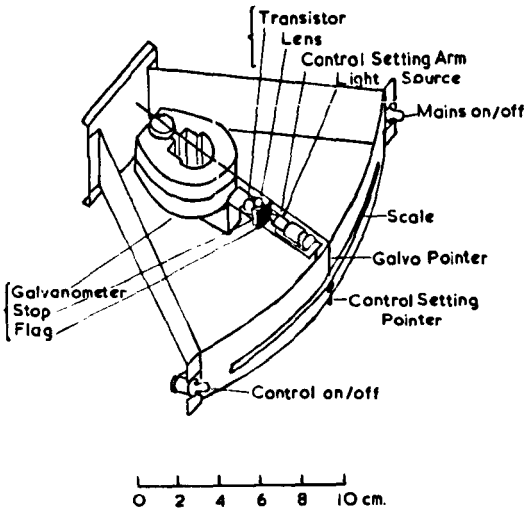


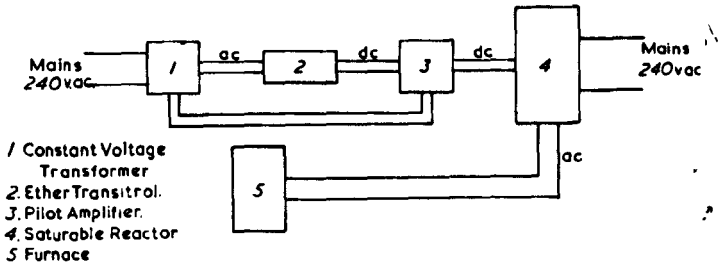
Figure 84. Sample Temperature - Original Controller, Initial Settings Slightly Varied.

measuring sample temperature. An Ether Transitrol Fully Floating Programme Controller (Gallenkamp's Cat. No FS 740) is used for the purpose instead. The furnace thermocouple is connected to this instrument. The mains supply to the windings is supplied through a Saturable Reactor with a series of numbered terminal pairs to vary the power output ranges. The temperature of the windings is compared, as before, with that set by a cam driven control. The movement of a "flag" attached to the galvanometer needle across the control pointer impedes the passage of light between a small source and a transistor, both of which are attached to the control (fig. 85 a). This occurs to an extent depending on the relative positions of the light source, "flag", and transistor. If the windings temperature is more than about 10° above that set by the control the "flag" is stopped at a position where it completely shuts off light to the transistor. If it is more than about 10° below that set by the control the "flag" is completely removed from the path of light. All stages between these two extremes occur and so the control is described as "fully floating". The power to the light source is passed through a Constant Voltage Transformer. The d.c. from the transistor passes into a Pilot Amplifier with four gain settings on the Proportional Band and hence into the Saturable Reactor where it adjusts the power to the furnace (fig. 85 b). The input to the Pilot Amplifier is also at a constant voltage.

A maximum d.c. input to the Reactor, and hence a.c. to the furnace, occurs when the "flag" is completely removed from the path of light to the transistor (when the windings are at more than 10° below that set by the control) and when the

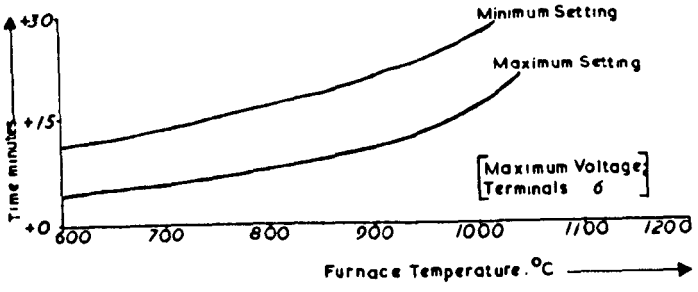


a. Mechanism.

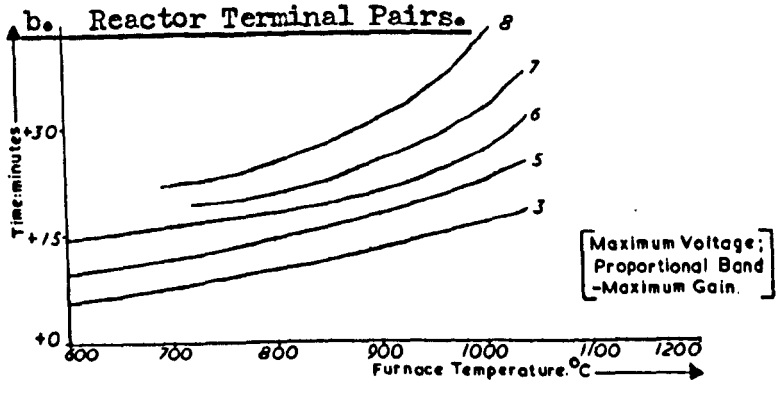


b. Circuit (simplified).

Figure 85. Ether Transitrol Controller.



a. Proportional Band.



b. Reactor Terminal Pairs.

c. Minimum Voltage; Terminals 6.

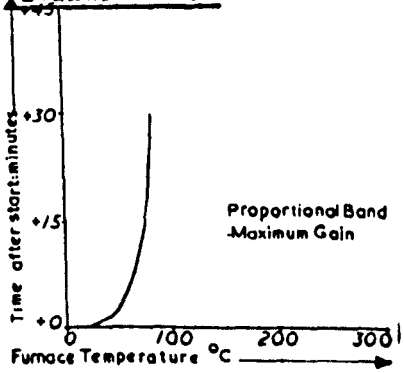


Figure 86. Control Tests with Furnace Temperature.

maximum gain is set on the amplifier. A minimum input occurs when the "flag" completely shuts off light to the transistor. The furnace power can be adjusted rapidly when necessary and the controller can "hold" the windings at a required temperature without delay. A heating cycle is, in fact, an infinite series of these fixed temperatures "held" by the controller. The maximum gain is set on the Pilot Amplifier to give full sensitivity to the system (fig. 86 a).

The windings resistance of the standard D.T. tube furnace was too large to maintain the required heating rate at the higher temperatures because the maximum power output from the Reactor was lower than that from the mains. The length of the windings was therefore reduced and the controller set to give maximum input to the furnace. A series of experiments were perform -ed taking the power off the different terminal pairs of the Reactor in turn and measuring the heating rates (fig. 86 b). Terminal pair 6 gave a heating rate of approximately 12.5°C/min over the range 1000°- 1100° C; this was sufficient to give a heating rate <u>inside</u> the furnace of 10°C/min and was therefore the most suitable. The system used for controlling the Gallenkamp's furnace heating rate is as follows:

a. Maximum Gain on Pilot Amplifier.

b. Furnace Input from Terminal Pair 6 in the Reactor.

c. Windings Resistance giving a power of 1.125 kw (40ft of Nichrome V wire, 22 s.w.g.).

The minimum power from this system is sufficiently small to "hold" the furnace heating rate at less than 10°C/min in the low temperature range (fig. 86 c); thus control was gained over the entire range. The windings and furnace thermocouple require to

be replaced from time to time. The shaping of the cam is considered in another section.

The Temperature Recording System. (fig. 87)

The Kent Multelec Temperature Recorder and Temperature Difference Recorder function as follows:

The e.m.f. in R2 is balanced with the dry cell R1 which is automatically standardised across a standard cell every 50 minutes of operation time in a normal Wheatstone Bridge potentiometric circuit. The galvanometer registers when R1 and R2 are out of balance. The circuit is automatically tested for balance as follows: the galvanometer is clamped and a pair of scissor feelers "chop" onto the needle every few seconds; if the potentiometric circuit is out of balance they operate a slidewire appropriately. This is attached to a pointer and pen which move across a calibrated chart and scale. The speed at which the chart rotates can be varied.

The resistance R2 is the temperature thermocouple in the case of the Temperature Recorder (fig. 87 a). Here when the furnace is being heated the millivoltage increase in this thermo-couple causes the circuit to be continuously slightly out of balance, and so the slidewire rotates during a cycle and the pointer moves up the scale. Kents advised that one thermocouple leading to both instruments and serving both the purposes of measuring sample temperature and temperature difference is liable to cause spurious effects in one instrument when the other is out of balance for any reason (fig. 87 c). Thus a sharp peak on the difference record may be the cause of a slight but important error on the temperature record at or near the peak temperature itself. Thus a separate crucible is used where possible.

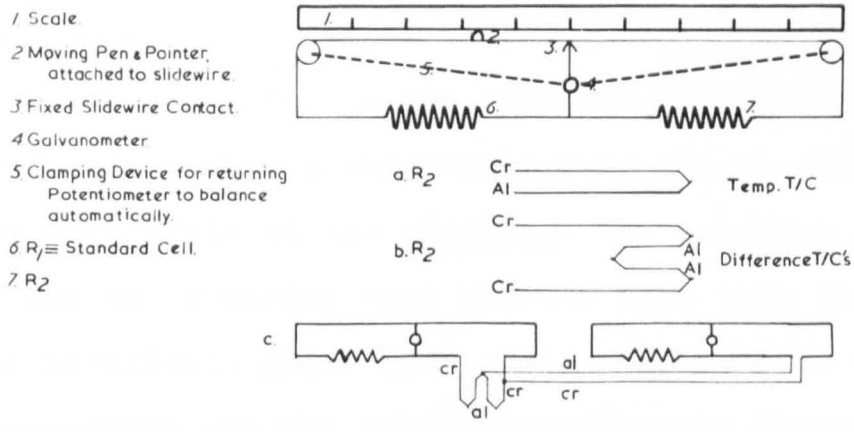


Figure 87. The Kent Multelec Circuit (Simplified).

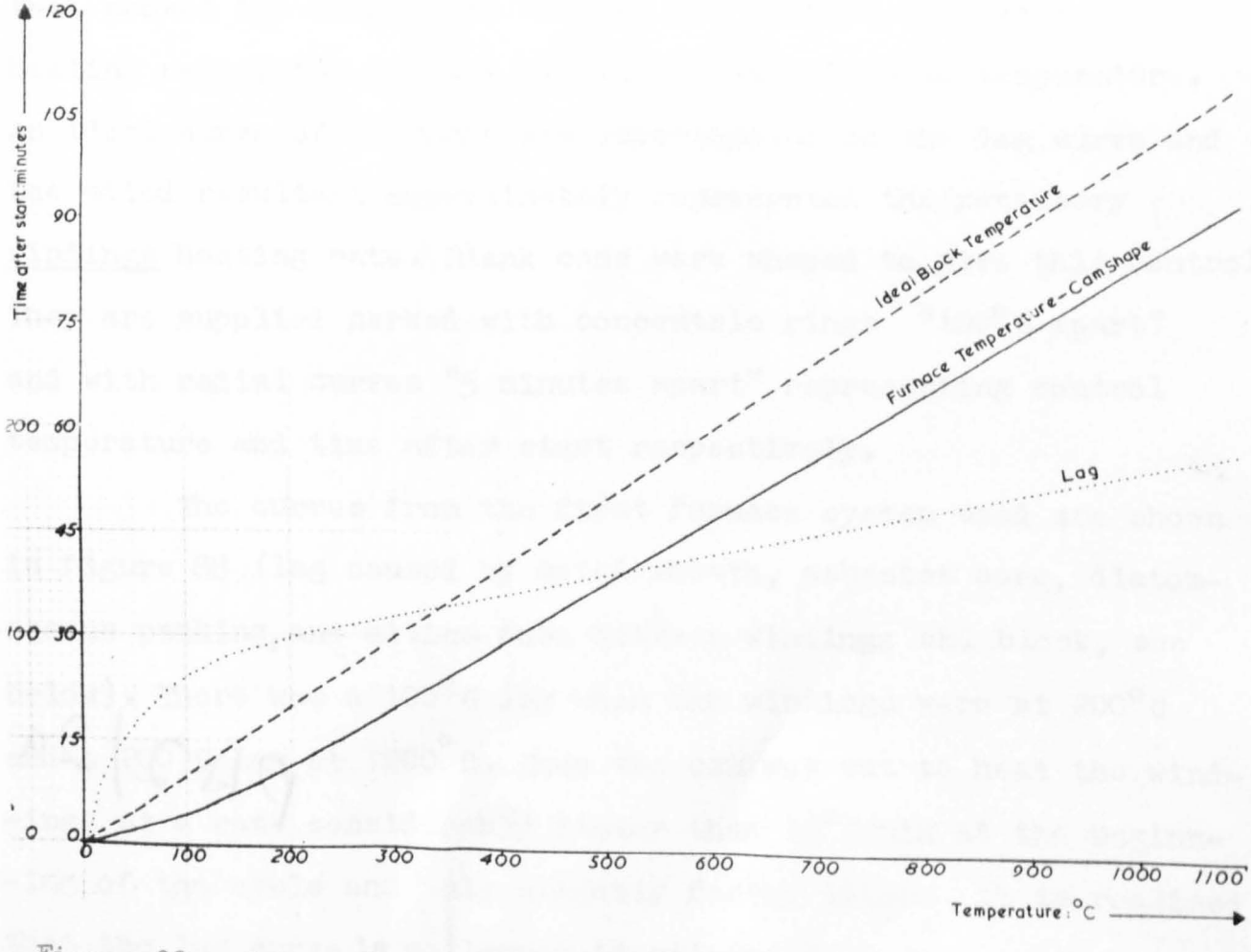


Figure 88. Curves Used To Calculate Cam Shape - First Furnace System.

The Sample Heating Rate and Shape of the Cam.

The cam was shaped to give a constant and reproducible sample (or block) heating rate of 10°C/minute as follows:

A second furnace thermocouple was placed beside the windings and was connected to the Temperature Recorder. The furnace was heated using a cam provided by Ethers which gave a rate of about 10°C/min at the windings. The readings on both the controller and the recorder were checked from time to time and found to be identical. After this cycle the furnace was cooled to room temperature and the sample thermocouple connected to the recorder again. The chart was turned back to the same starting point as before and a second identical cycle started. The chart then showed the comparison between the furnace and block heating rates; the lag was plotted against furnace temperature. An ideal curve of 10°C/min was superimposed on the lag curve and the added resultant approximately represented the necessary windings heating rate. Blank cams were shaped to give this control. They are supplied marked with concentric rings "100°C apart" and with radial curves "5 minutes apart" representing control temperature and time after start respectively.

The curves from the first furnace system used are shown in figure 88 (lag caused by metal sheath, asbestos core, diatom-aceous packing, and silica tube between windings and block, see below). There was a 100°C lag when the windings were at 200°C and a 200°C lag at 1200°C. Thus the cam was cut to heat the wind-ings at a rate considerably faster than 10°C/min at the beginn-ing of the cycle and only slightly faster later. It is realised that the lag curve is no longer identical after these alterations but the result is a satisfactory and reproducible heating rate

of approximately 10° C/min (fig. 89 a). This same method was applied to each of the furnace systems used. The resulting sample heating rate for Block No. 2 and the furnace system used in the main work is shown in figure 89 b.

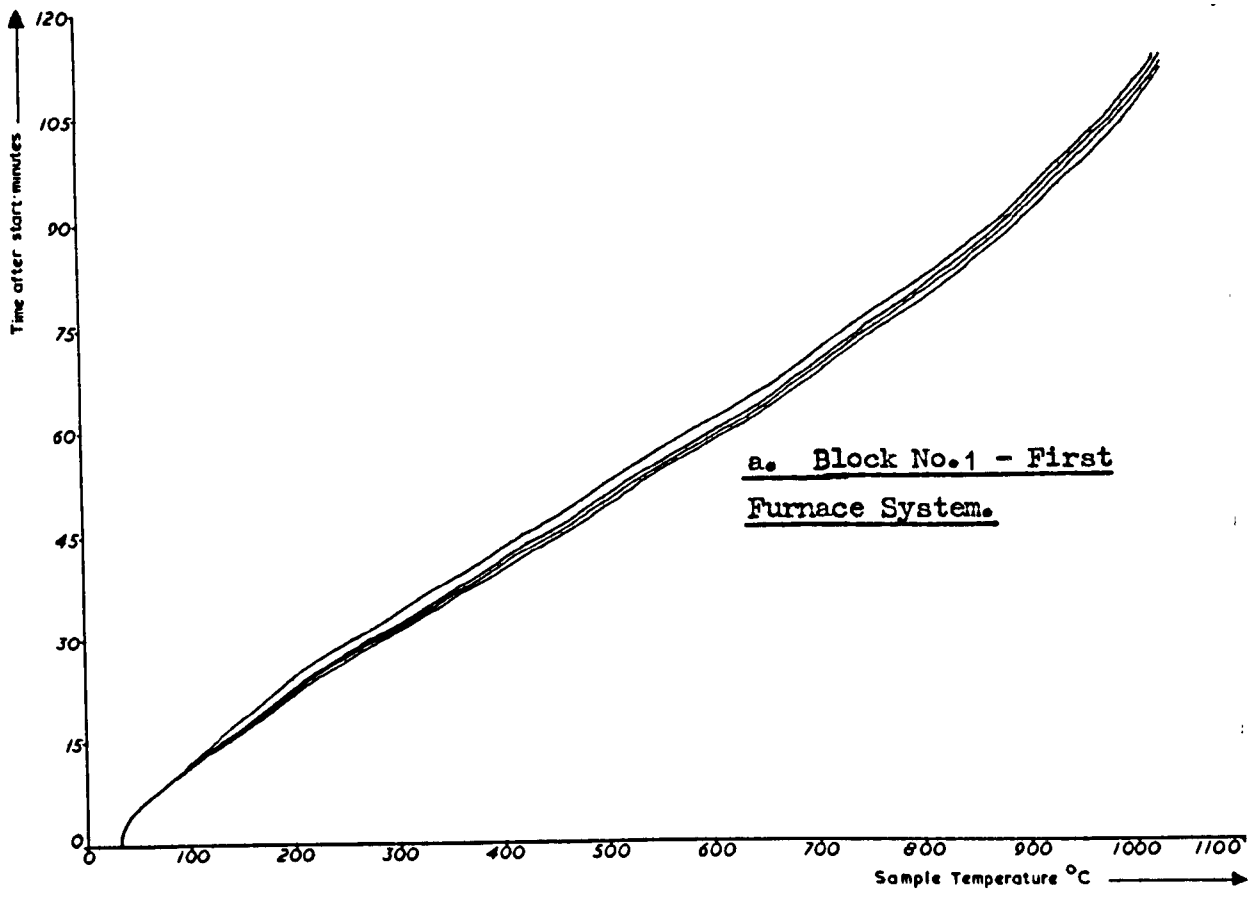
The Temperature Difference Recording System.

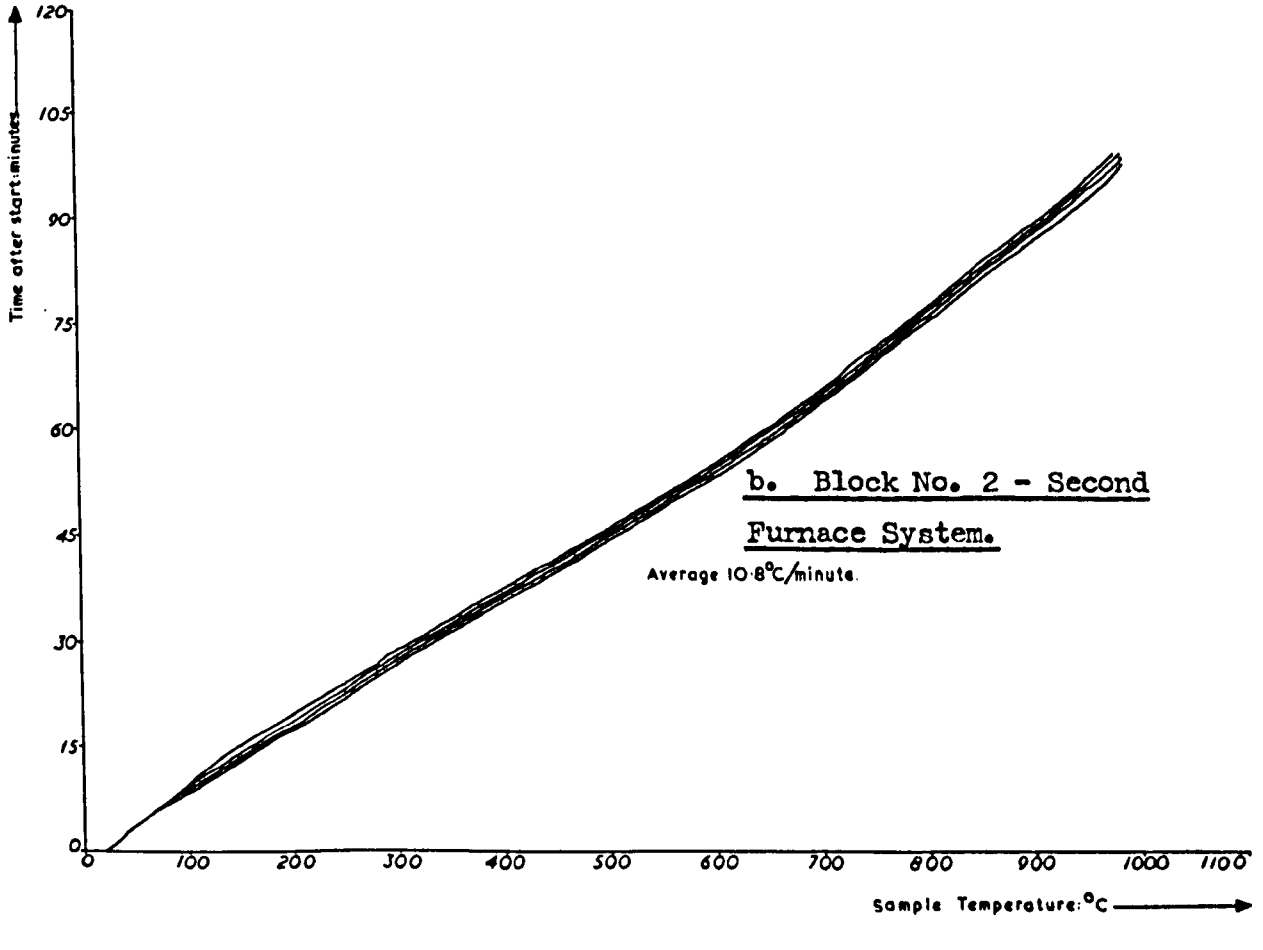
The Difference Recorder is similar in principle to the Temperature Recorder. Here R2 is is the difference thermocouple system (fig. 87 b) and the pointer is in the middle of the scale when the millivoltages in the two thermocouples are identical. A millivoltage difference between the thermocouples is recorded by the pointer moving left or right to rebalance the potentio--metric circuit. The half scale deflection in the original app--aratus was 75° - 0 - 75° which was too low a sensitivity for present purposes. Thus an electronic modification was fitted to amplify the millivoltage difference between the thermocouples. Three choices of half scale deflection are now available: 5° - 0 - 5°, 20° - 0 - 20°, and 40° - 0 - 40°. This amplifier is run off the Constant Voltage Transformer and it is necessary to balance it for each scale of sensitivity as follows:

Thermocouple input is reduced to zero by the two gain controls. The "Balance" screw is turned until the instrument is balanced (pointer stationary) at all points on the scale; this ensures that there are no spurious effects generated by the amplifier itself. The "coarse" and "fine" gain adjustment screws are turned until the instrument gains balance in the minimum number of steps without overshooting the middle of the scale.

One further modification was made because it is necessary to have a rapid check of sample temperature on the difference record. The Temperature Recorder on the old apparatus gave

Figure 89. Reproducibility of Sample Heating Rate.

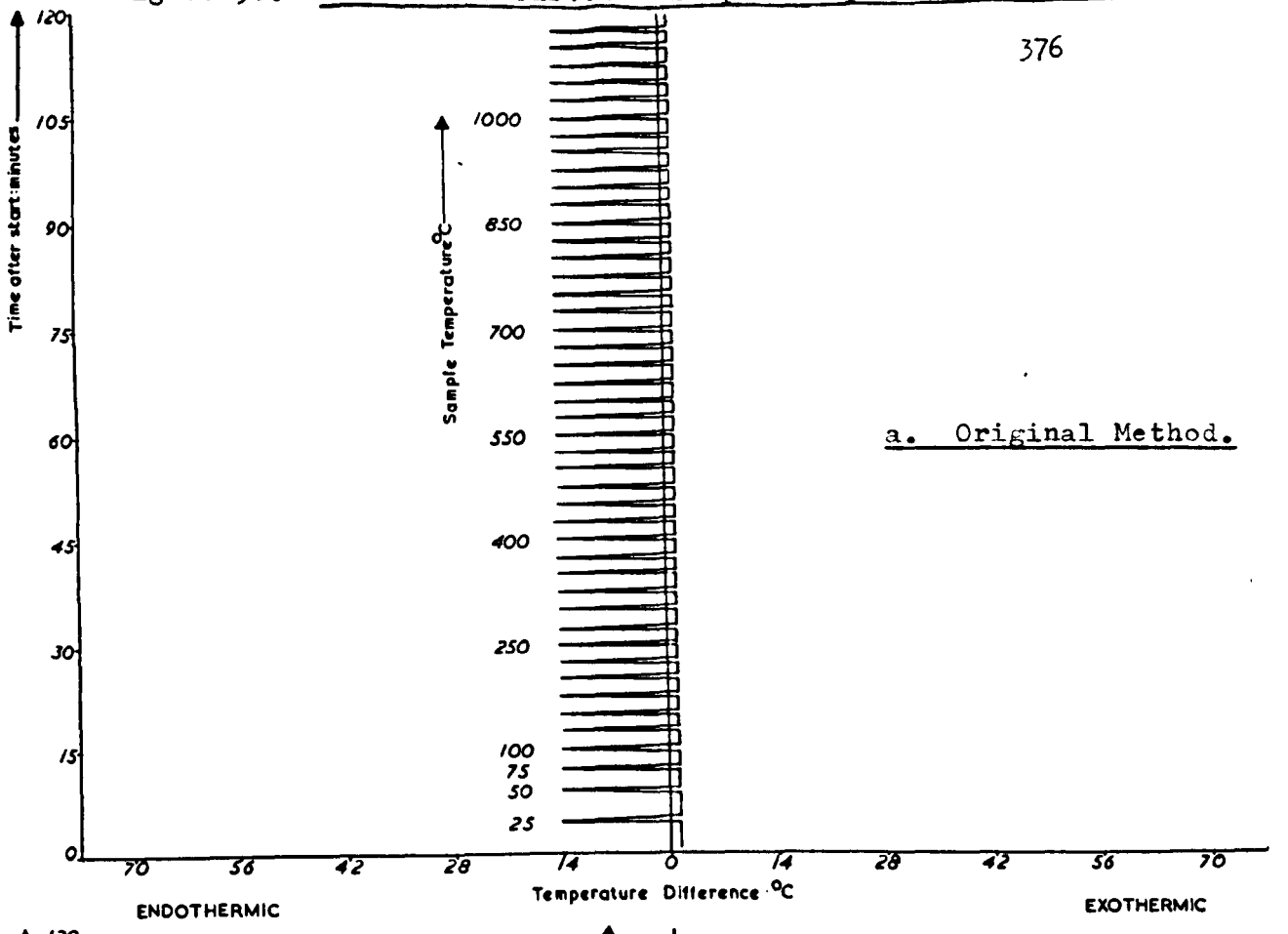




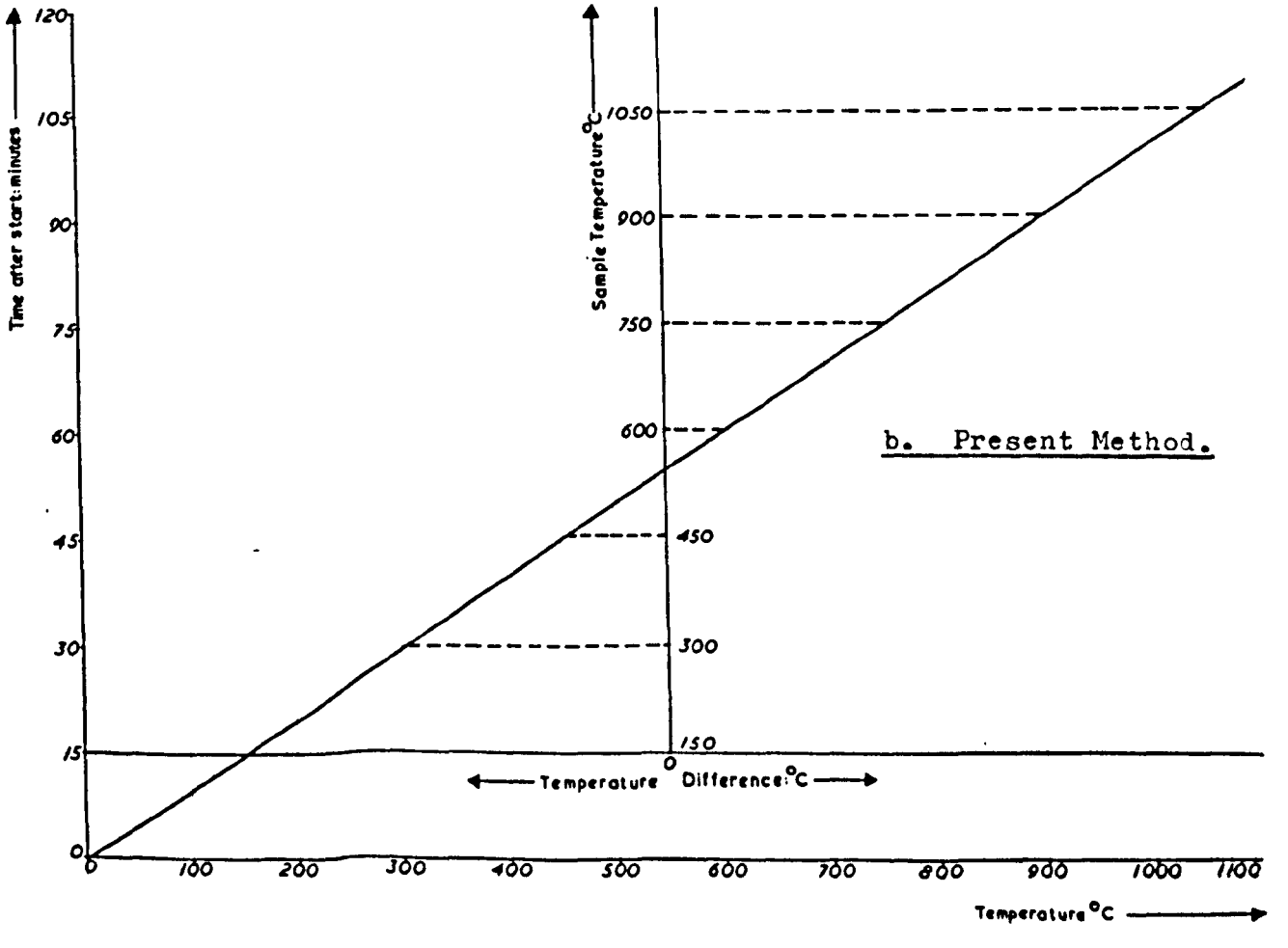
impulses to the Difference Recorder at intervals of 25° C; these caused small sharp deflections on the difference record (fig. 90 a). This method may have led to errors in interpretation of the curves, particularly over the small range of sharp peaks. Thus it was decided to eliminate these impulses and to check the sample temperature on the difference record by having both charts running at the same speed (fig. 90 b). This was not possible originally so the instrument was fitted with a new gear box similar to that in the Temperature Recorder. Three choices of chart speed are now available on each: 4 inches, 8 inches, and 12 inches per hour.

The difference recording technique gave some difficulty. The millivoltage generated in the two thermocouples should be identical when there is no diagnostic temperature difference between the contents of the two crucibles (or no drift of the base line when there is inert in both). First it was thought to be necessary to eliminate e.m.f's generated by effects other than the temperature difference between the hot junctions and the cold junctions such as those induced by the furnace windings, Saturable Reactor, or the electric motor coils of the recording instruments. Thus the furnace tube was sheathed with high temperature nickel alloy (inconel) which absorbed e.m.f's induced by the windings (Mitchell and Mackenzie, 1959). The thermocouples themselves may be sheathed with metal insulation (Collins, personal communication, 1961). However, it was pointed out that the Multelec instruments are fitted with a device to filter out a.c. from the thermocouple input. Second it is important to use difference thermocouple pairs generating e.m.f's as similar as possible at identical temperatures. Thus each pair is of the

Figure 90. Difference Curves - Sample Temperature (diagrammatic).

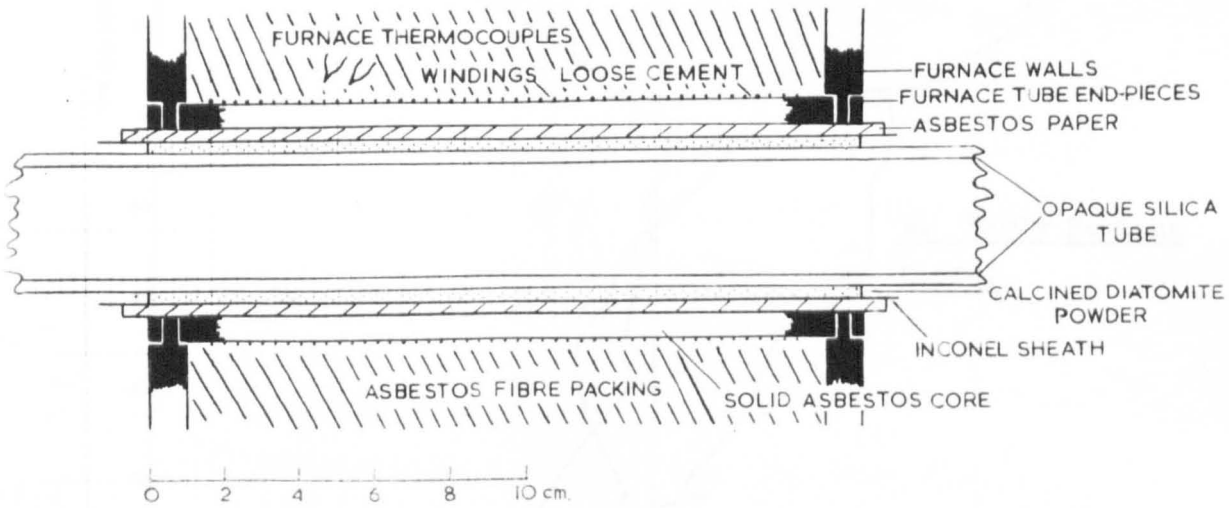


a. Original Method.

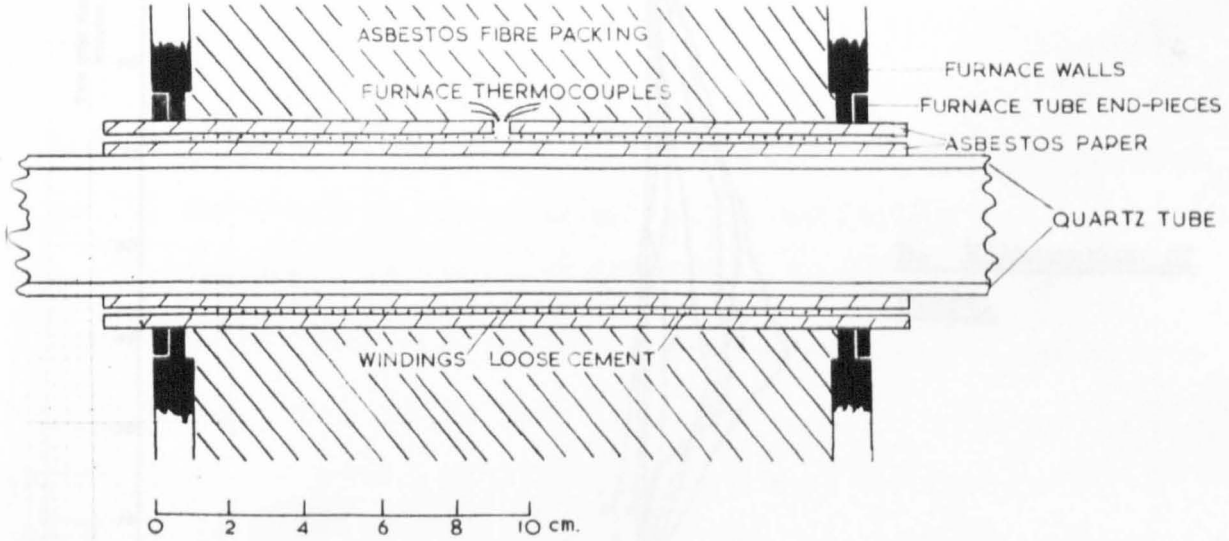


b. Present Method.

same age because metal resistance alters considerably after heating (Berry and Martin, 1959), is the same length, is from the same batch of metal wires, and with similar welds and/or twists at the hot junctions. Third it is important that the thermocouples and crucibles are symmetrical about the heat supply inside the tube. The first furnace system used (fig, 91 a) was the cause of errors in this respect. The diameter of the silica tube was smaller than that of the inside of the core so diatomaceous powder and asbestos paper packing were necessary for fitting, as well as the inconel sheath (Mitchell and Mackenzie, 1959). It was difficult to pack this uniformly and generally the heat supply to the silica tube, block, and crucibles was unsatisfactory (fig. 92 a). Thus a second furnace system was used (fig. 91 b): a single layer of wet asbestos paper was wrapped around the central part of the silica tube and allowed to dry, the 40 feet of Nichrome wire were wound tightly around this, the gaps were filled with diatomaceous cement (this dried as a powder to facilitate dismantling the furnace for rewinding), and a second layer of asbestos paper was wrapped around the windings. The two furnace thermocouples were fastened tightly alongside and the core was packed into the frame of the furnace as before. This system gives a more uniform heat inside the tube (fig. 92 b). But the cylindrical blocks were slightly loose when in position and it is important that each is central when used. Finally the hot junction beads of the thermocouples must be in the middles of the crucibles. A rapid test for asymmetry of the thermocouples with respect to heat input is to manipulate the controller by hand to accelerate it suddenly at a temperature over 900°C. The tube and block are "saturated" with heat and the "burst" passes very



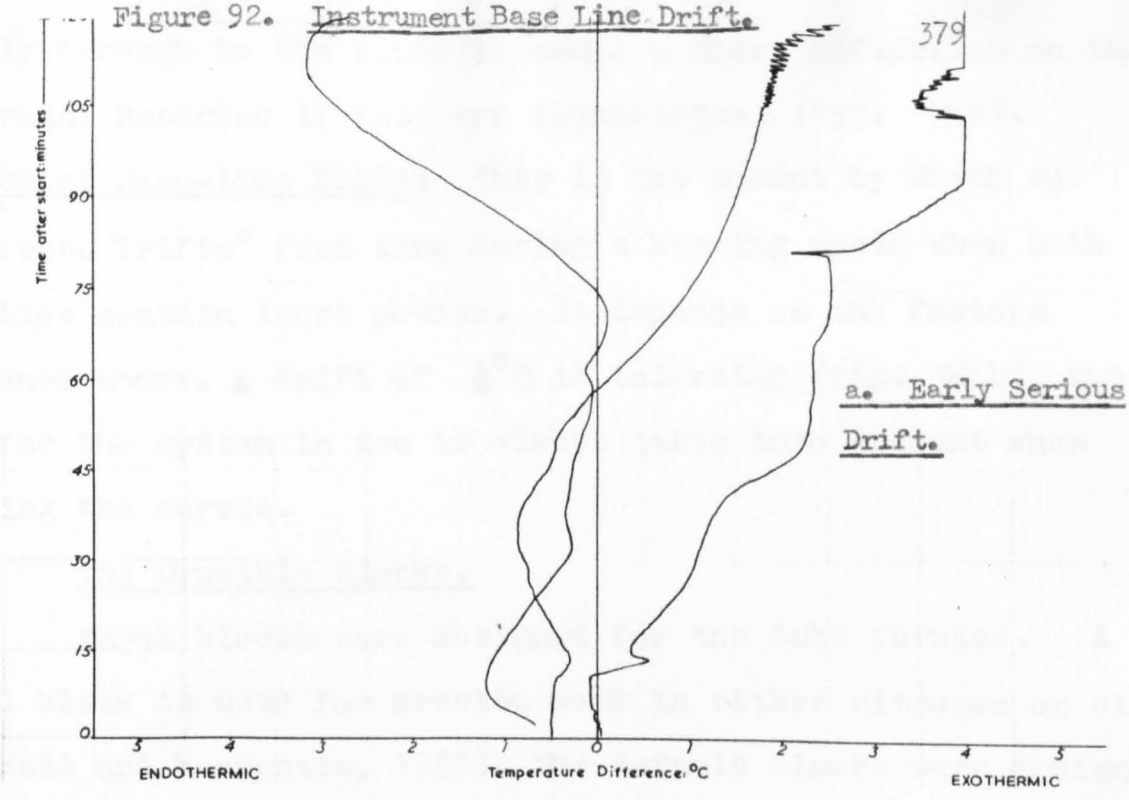
a. First System.



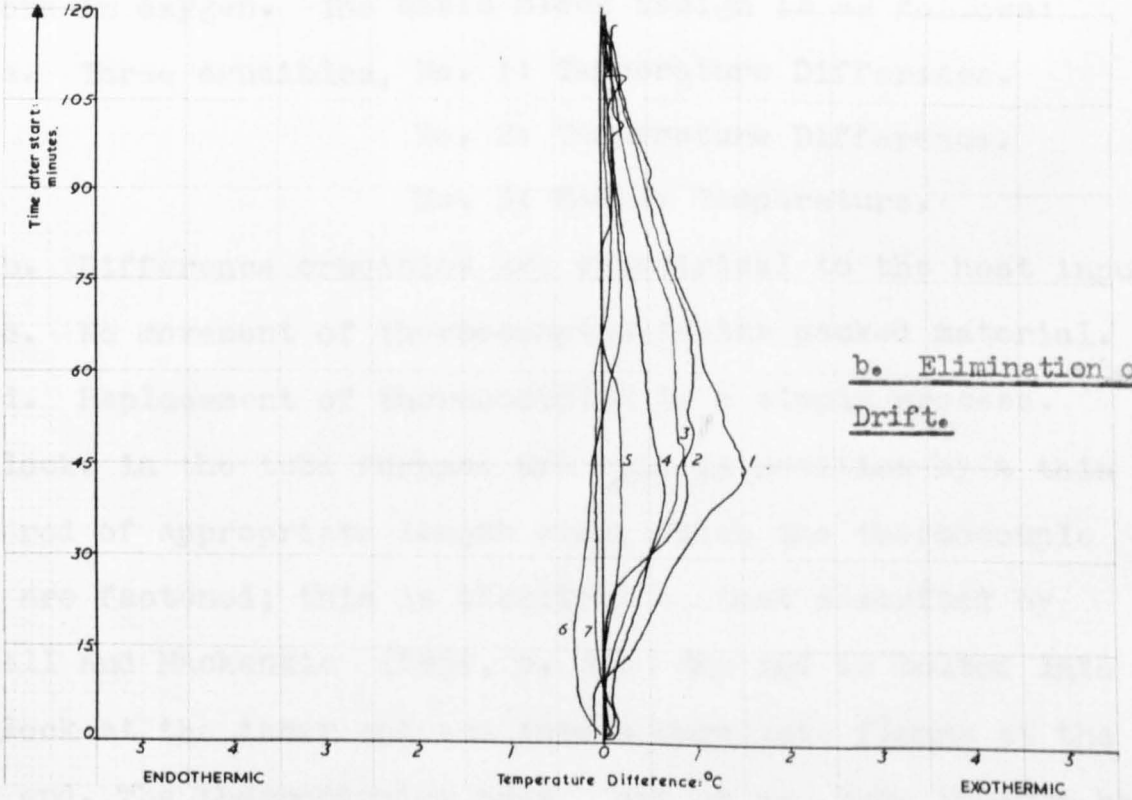
b. Second System.

Figure 91. Furnace Packing Systems.

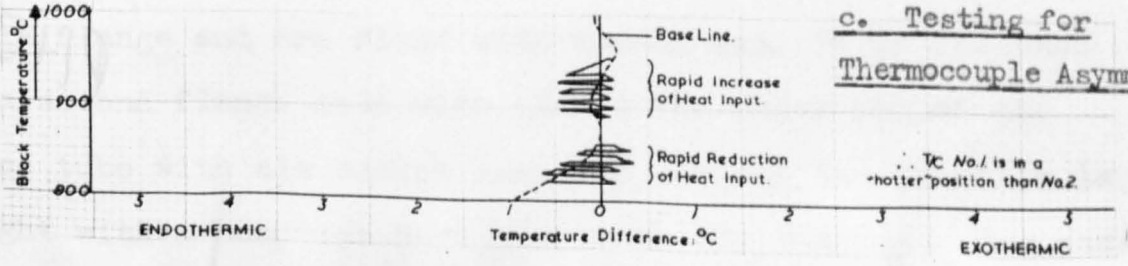
Figure 92. Instrument Base Line Drift.



a. Early Serious Drift.



b. Elimination of Drift.



c. Testing for Thermocouple Asymmetry.

rapidly through to the block to cause a sharp deflection on the Difference Recorder if they are asymmetrical (fig. 92c).

Instrument Base-Line Drift: This is the amount by which the difference "drifts" from zero during a heating cycle when both crucibles contain inert powder. It depends on the factors mentioned above. A drift of $\frac{1}{8}^{\circ}C$ is tolerated (fig. 92b) but that for the system in use is always taken into account when studying the curves.

The Crucible Blocks.

Three blocks were designed for the tube furnace. A nickel block is used for precise work in either nitrogen or air (Mitchell and Mackenzie, 1959). The ceramic blocks were designed for work in oxygen. The basic block design is as follows:

a. Three crucibles, No. 1: Temperature Difference.
No. 2: Temperature Difference.
No. 3: Sample Temperature.

b. Difference crucibles are symmetrical to the heat input.

c. No movement of thermocouples inside packed material.

d. Replacement of thermocouples is a simple process.

The blocks in the tube furnace are held in position by a thin steel rod of appropriate length along which the thermocouple leads are fastened; this is identical to that described by Mitchell and Mackenzie (1959, p. 35). The rod is bolted into the block at the inner end and into a duralumin flange at the outer end. The thermocouples pass out of the tube through holes in this flange and are fixed with vacuum wax. It is fastened onto a second flange held with wax at the outer end of the furnace tube with six socket head cap screws; the junction is airtight with a neoprene O-ring between the flanges. Gas passes

into the furnace through a short tube in the outer flange (fig. 93 a).

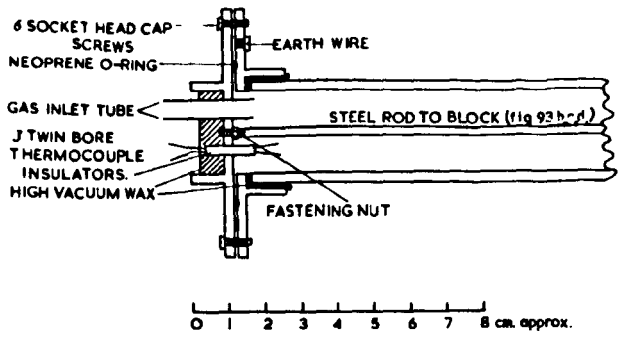
Block No. 1 (fig. 93 b). This was used for experiments with techniques before the routine analyses were started. The small removeable block is of nickel; two metal plugs here fitted into appropriate holes in the ceramic body of the block. Unfortunate--ly the ceramic material wore rapidly and the block no longer fitted tightly so wire was held around the block keeping the components firm. N.B. Crucible No. 3 is not packed with inert neccssitating slight recalibration.

The advantage of this design is the removeable crucible block though final packing is done after replacement of the crucibles. The disadvantage is that the ceramic material was brittle; harder ceramic material, however, is difficult to machine.

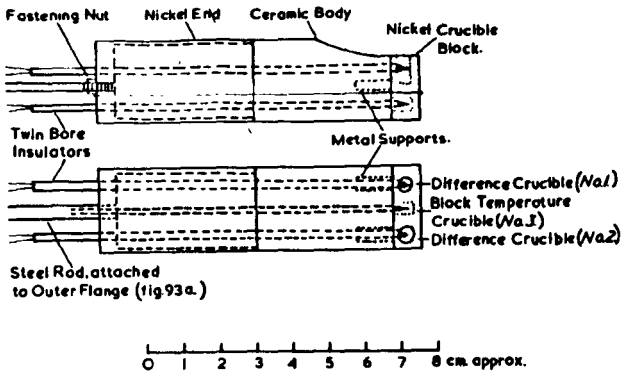
Block No. 2 (fig. 93 c). This is used for the routine analyses. Its advantages are that the "sample" temperature is taken from packed inert material and, more important, the block is more durable. The disadvantage is that cleaning and repack--ing the crucibles is more of a strain on the untwisted thermo--couple hot junctions; this leads to a number of breakages. A compressed air gun is used to clean the crucibles after each analysis quite satisfactorily.

Block No. 3 (fig. 93 d). This has not been made at this stage because a suitable ceramic material has not been found.

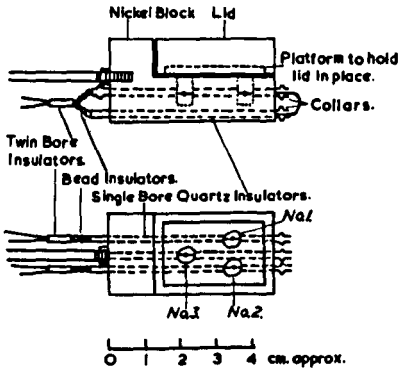
A convention used is as follows: An Endothermic reaction in the sample (thermocouple No. 2 is hotter than No. 1) causes the difference curve to move to the left on the chart and vice versa for an Exothermic reaction.



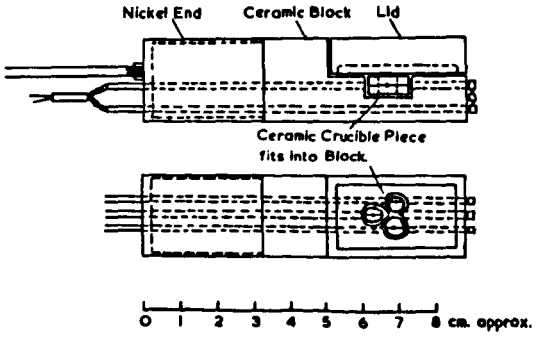
a. Flanges on the Furnace Tube.



b. Block No. 1.



c. Block No. 2.



d. Block No. 3.

Figure 93. Machined Parts in the Differential Thermal Apparatus.

(not to scale)

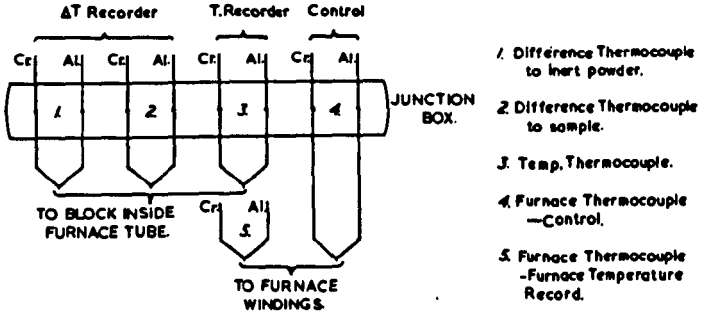
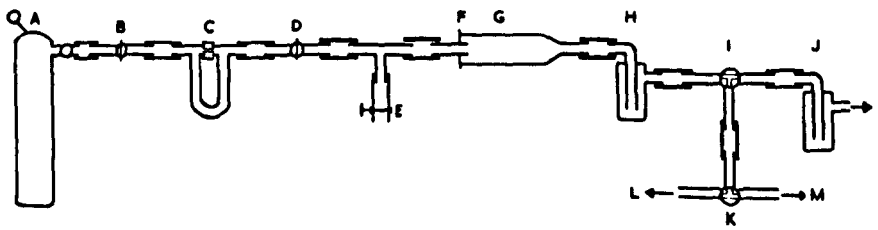


Figure 94. The Thermocouple Circuit.



A Gas Cylinder
B & D. Stopcocks
C Capillary Flowmeter.
E Hoffman Clip.
F Vaccuum-sealed Flange.
G Furnace Tube
H & I Absorption Flasks.
I & K. Three-way Stopcocks
L to Vaccuum Guage
M. to Vaccuum Pump

Figure 95. Furnace Atmosphere Controlling System.

The Thermocouples. (fig. 94)

There are two furnace thermocouples, two difference thermocouples, and one temperature thermocouple. They are of Chromel/Alumel wire, 26 s.w.g. These alloys are satisfactory up to temperatures of 1200 C though they become brittle after use. The thermocouples are always three feet long; this is important, first for the furnace couple to the controller where an adjust-ment is made for its resistance, and second for the difference couples (see above), and third for reproducibility of the temperature couple. The ends of the appropriate wires are twisted firmly together and the tip subjected to carbon arc welding for a few seconds; this is done in the Chemical Engineering Dept., U.C.

The leads terminate at a junction box and those from here to the instrument are of the same alloys and do not need replacing. Chromel leads are connected to positive instrument terminals, alumel to negative. There are Cold Junction Compensation Coils in both the controller and temperature recorder to adjust automatically for ambient temperature variations from the freezing point of water (the difference recorder is balancing two e.m.f's in the same ambient temperature). The alloy/brass contacts in the junction box do not cause spurious effects under normal conditions

The thermocouple leads are insulated in the furnace by twin bore ceramic insulating tubes and outside by coloured flexible fibre glass tubes; the colours are yellow for chromel leads and black for alumel leads. Quartz tube insulators are used to insulate the wires inside Block No. 2. This material was softened by heating and pushed up into "collars" (fig. 93 c).

The Apparatus for Controlling Tube Atmosphere. (fig. 95)

This is similar to that described by Mitchell and Mackenzie (1959). A vacuum of 0.05 mm mercury could be pumped with this system.

The Inert Material.

Kaolinite calcined at 1600°C for 48 hours termed "Superfine Molochite" (English Clays, Lovering Pochin and Co. Ltd.) was used throughout. A test in the centrifuge showed that all this material was finer than 0.002 mm.

Standardised Apparatus Procedure.

a. The block is fastened tightly inside the furnace tube with the six flange screws (fig. 93 a).

b. The furnace is disconnected from the controller.

c. The cam is fastened into the controller and the switch off point adjusted with the red pointer on the scale. The pointer is then moved down the scale to register the same as the galvanometer. The cam driving motor switch is turned off (fig. 83)

d. The recording pens are lifted from the charts.

e. Gas is passed through the furnace tube as follows: The stopcock D (fig. 95) is opened, the three way stopcock I is adjusted to connect absorption flasks H and J (isolating the vacuum pump and guage). The gas cylinder A is turned on and the outlet pressure adjusted to 2 lbs/sq. in, the stopcock B is carefully manipulated to give a flow of 200 ml/min (approximately 17 cms difference in the Flowmeter water levels). The gas flows through the system and bubbles out at absorption flask J.

f. Air and water vapour in the system are evacuated as follows: The stopcock D is closed, the three way stopcocks I and

K are adjusted to connect the vacuum pump to the the furnace tube and the vacuum guage together (isolating the absorption flask J). The pump is switched on for a few minutes and water vapour can be driven out of the furnace tube, if necessary, by gently heating with a bunsen flame.

g. While the system is being isolated the instrument is switched on at the mains, the dry cells are connected, the recorders switched on, and the pointers allowed to settle.

h. Mechanical twist in either of the galvanometer hair suspensions can be detected by depressing the "Galvo Zero" buttons; they are adjusted if necessary.

i. The dry cell "Standardising Buttons" are depressed until the pointers stop moving.

j. The chart speed gear box levers are checked.

k. The furnace atmosphere is finally controlled as follows: The vacuum in the system is checked on the guage and, if satisfactory, the three way stopcock K is turned to a half way position to hold the vacuum between D and K; the pump is switched off. D is carefully manipulated to replace the vacuum by gas flowing through C; the three way stopcock I is finally adjusted to allow the gas to flow out through J. The Hoffman Clip E can be used for quick release of the vacuum if necessary.

l. The charts are appropriately marked and the chart pens are replaced; they are turned to the starting point. Both charts start at similarly numbered lines.

m. The cam driving motor switch is turned on and the furnace connected to the controller.

n. The charts and gas flow are checked occasionally.

o. When the controller has automatically switched the instrument off at the end of the heating cycle, the gas and the mains are both switched off at source, the apparatus is allowed to cool to about 600°C, and the block removed for more rapid cooling. The block returns to room temperature in about an hour and is cleaned and repacked in preparation for the next analysis while the furnace is cooling. N.B. Hot air may be pumped off with the vacuum pump on the open ended tube.

The Wiring Circuit.

The Gallenkamp's tube furnace system described above is used for all the analyses in the present work and a set of standard curves was made for this purpose. Other analyses were being performed concurrently by members of this department and the Catterson - Smith furnace (fig. 82 b) was used for this purpose; a second set of standard curves was therefore necessary. The only modifications required here were as follows: a two way switch was put in the controller - furnace circuit, small interchangeable single socket plugs were used in the junction box for the thermocouples and leads to the instruments, a second cam was shaped as before, and the terminals marked 3 in the reactor were used for obtaining a heating rate of 10°C/minute in the second furnace.

Figure 96 shows the complete wiring diagram.

Figure 97 shows the complete apparatus.

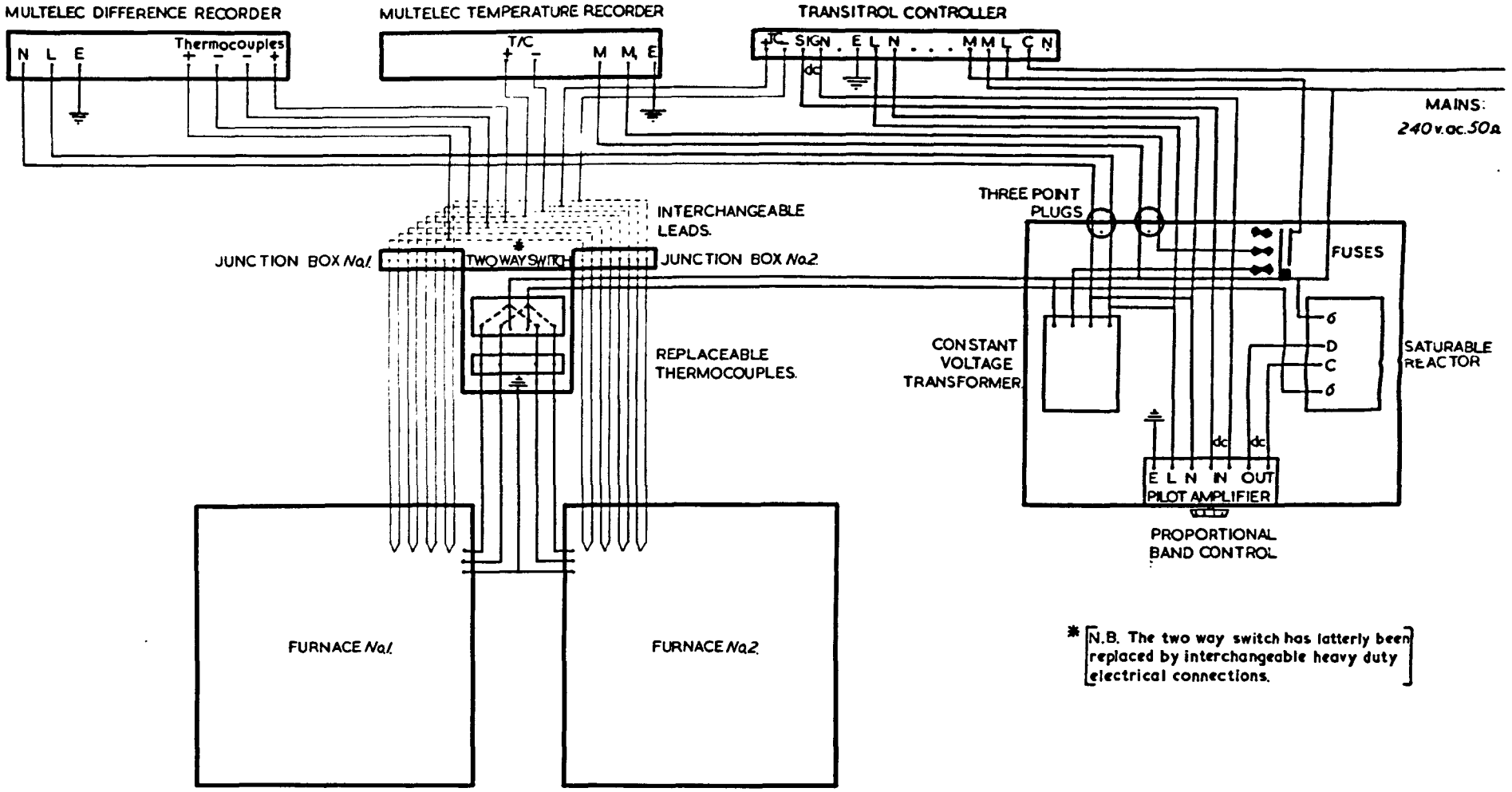


Figure 96. Wiring Diagram for the Completed Differential Thermal Apparatus.

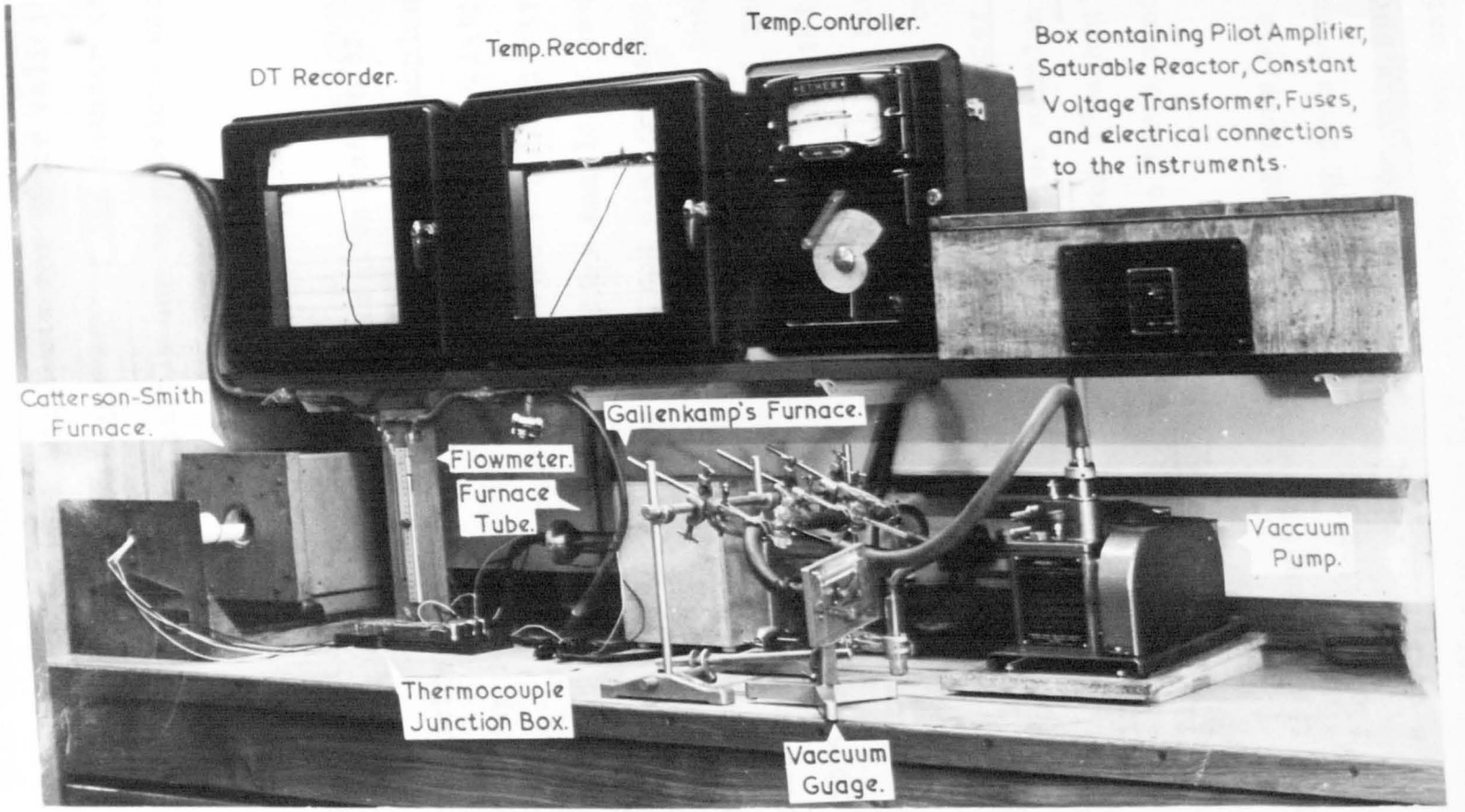


Figure 97. The Completed Differential Thermal Apparatus.

Chapter 25. Differential Thermal Techniques.

This chapter comprises a discussion of the techniques used in the D.T. work and tests for their validity. The standard procedure outlined at the end of the chapter is partly due to tests done here and partly due to previous work by other authors.

Pretreatment of Specimens.

This section is concerned with the preparation of unconsolidated specimens for D.T. analysis; the rock samples are not pretreated other than by crushing and bringing to relative humidity. The silt and clay fractions of unconsolidated material are studied separately and so a representative sample of each is required. The method for separating silt from clay is based on the differential settling velocities of particles larger than and smaller than 0.002 mm in a liquid medium assuming Stokes' Law (Truog et al, 1936; Mackenzie, 1955; Hillier, 1955). In this work the bulk samples for separation consist of particles finer than 0.422 mm (fig. 81); for convenience all the material between 0.002 and 0.422 mm is referred to as "silt" in the remainder of this section only. The separation of representative samples of the two fractions requires that all the clay is removed ("washed") from the settled silt before completion. There are three conditions for this:

a. That the suspensions are in a state of complete dispersal because flocculation tends to remove clay from suspension with the silt. If a dispersing agent is required for this purpose as it is here it should alter the D.T. properties of the material by a minimum, it should be expedient to use, and easily removed

before drying the separated fractions. Ammonia solution is preferred to calgon for this reason.

b. That the entire volume of supernatant liquid which contains the clay remaining in suspension is removed after the required settling period as in the centrifuge (see Chapter 6). In the methods described by Mackenzie (1955) using quart milk bottles, and by Hillier (1955) using large plastic settling cylinders, a proportion of the clay is below the 10 cms mark (the crucial level in each case) when settling starts. In cases where certain minerals in the clay fraction settle faster than others; non representative samples are produced. In this respect it was noted that a small proportion of silt was removed with the super-natant liquid each time and so a small depth was left behind.

c. That separation continues until the supernatant liquid is essentially clear after the required settling time. This entails shaking up the settled material into fresh suspensions several times for each suspension. In fact the supernatant liquid can never be completely cleared because some clay always settles out. Here ten settling periods were always found to clear these suspensions effectively.

N.B. Errors due to deviations from Stokes' Law assumptions such as ambient temperature fluctuations, S.G. of particles, and their flakiness are inherent in any method of separation by settling.

Calculations involved in using a centrifuge for separations are found in Chapter 6 . This method is quick but tedious and the short spinning times involved leave little margin for error. It is not normally used but it is stated when it is. Instead a method using 2 Litre Aspirator bottles was

devised:

Calculations for the depth of suspension in the bottles and the time allowed for settling were made from Stokes' Law for distilled water at 20° C.

a. 9.30 a.m. to 5.00 p.m. (7½ hours), depth 9.7 cms.

b. 5.30 p.m. to 9.00 a.m. (15½ hours), depth 20 cms.

Thus a mark was made on each of a dozen 2 Litre Aspirator bottles 9.7 cms above the tubulure (which is 0.5 cms above the bottom). The bottles are filled with suspension to this mark for the day time settling period and being only 20 cms deep they are filled to the top for the overnight settling period. The tubulures are connected to one foot lengths of rubber tubing closed with Mohr Clips; rubber stoppers are placed loosely in the necks. Twelve 3 Litre Winchester bottles are left below the shelf to hold the supernatant liquid (fig. 98). The Winchesters are nearly full of clay suspension after two washings; this is neutralised with a few drops of 9N acetic acid (phenolphthalein indicator) and flocculated with 20 ml magnesium chloride solution. The clear liquid bulk is syphoned off leaving room for further washings. After ten washings (one week) the flocculated clay is washed out of the Winchesters and decontaminated by centrifuging four times in absolute alcohol (silver nitrate tests showed that this removed all the chloride) before drying at 50° C and hand pulverising. The "silt" is washed out of the settling bottles and dried at 50° C; it is brushed through Sieve Mesh 240 and the two fractions stored separately.

The final phase of pretreatment is the process of standardising the specimens for four days in a vacuum dessicator at 56% relative humidity by standing over a saturated solution of

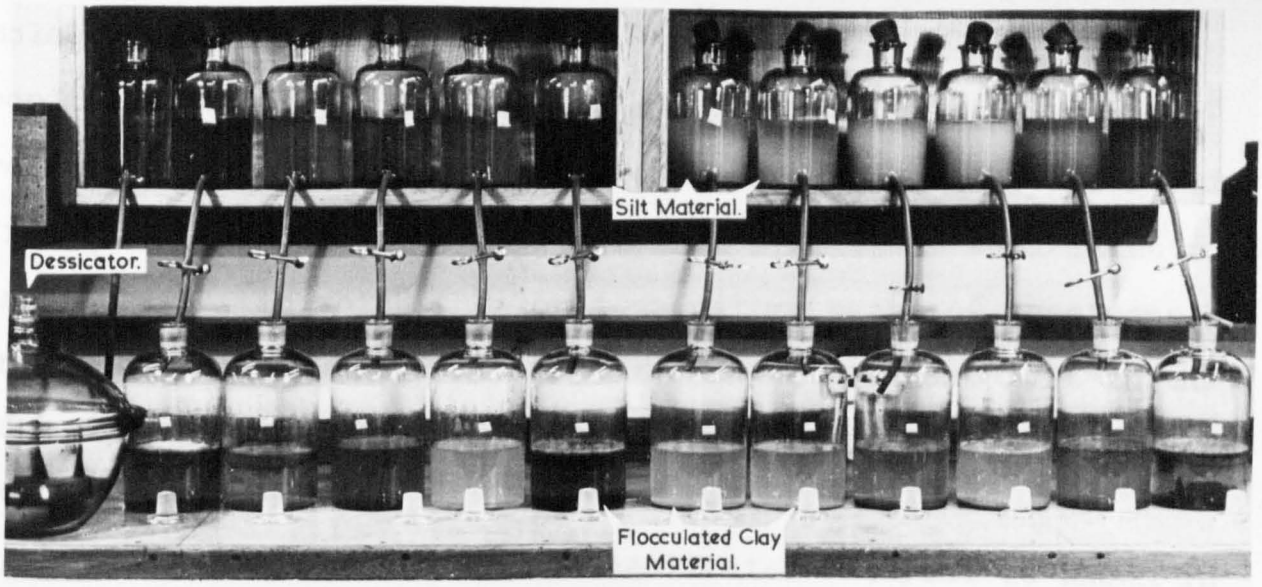


Figure 98. Separation of Silt and Clay Grades.

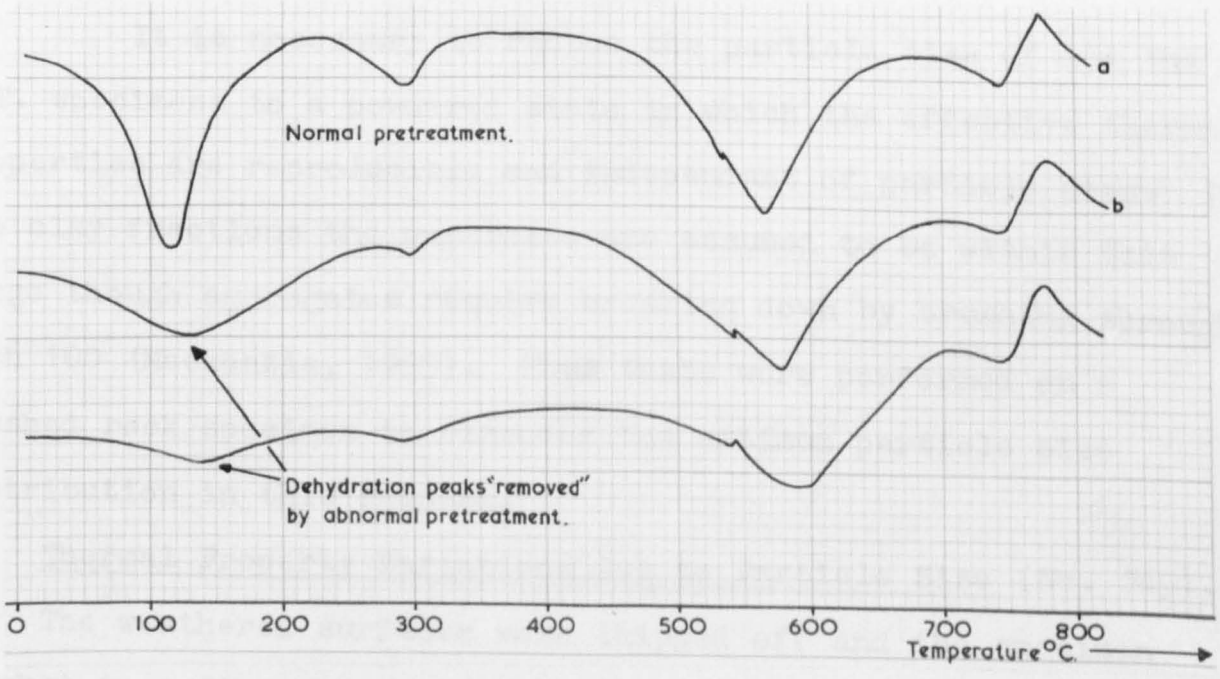


Figure 99. Pretreatment - Relative Humidity. (Rusty Clay Sample No. 185; normal analyses)

magnesium nitrate (hydrated). This process is to ensure that the molecular water in each case has been retained under identical conditions and that low temperature peaks of dehydration are reproducible. The specimens are analysed immediately after removal from the dessicator. The need for this process is well illustrated in figure 99 in which the low temperature peaks of specimens b and c have nearly been eliminated because they were left in the furnace for about 20 minutes at 50° C before analysis; specimen a was analysed normally.

The flow sheet for unconsolidated material is shown in figure 100 .

Particle Size of Specimens.

It is necessary to reduce the particle size of all the D.T. specimens to a powdered state in which the effective thermal properties are reproducible and independant of particle size. In the clay fractions the particles are assumed to be within this range though aggregates require breaking down by brushing through Mesh 100 (Mackenzie, 1955). Thus tests were performed on a crushed rock specimen to discover the optimum particle size distribution in this respect.

Thermal Property Variations due to Particle Size (No. 949).

The weathered surfaces were chipped off and the specimen crushed to a fine sandy texture in a roller crushing machine. A small quantity of this was pulverised with an electrically operated pestle and mortar (the flow sheet for these tests is shown in figure 101). It was required to know the length of time for which this sample needed to be pulverised before its effective thermal properties became constant. It is a hard tuff and taken as representative.

Dry Subsample - Material 0.422 mm (fig. 81)

Disaggregated with stiff brush

Repeated ten times:

- Suspended in Distilled Water up to appropriate mark on two - litre Aspirator Bottle
- 40 drops of NH_4OH added; Shaken vigourously
- Allowed to Settle for the appropriate Settling Period
- Supernatant liquid removed; stored in three - litre Winchester Bottle
- Appropriate volume of Water and NH_4OH added
- Shaken vigourously

Coarse Material

Fine Sand

M240

Dried at 50° C.

56% Relative Humidity

Silt Fraction ready for Analysis

Repeated when necessary

Bulk Supernatant Suspension

Neutralised with 9N Acetic Acid

Flocculated with 20 ml 2N $MgCl_2$

Clear supernatant liquid removed, washed in alcohol

Dried at 50° C.

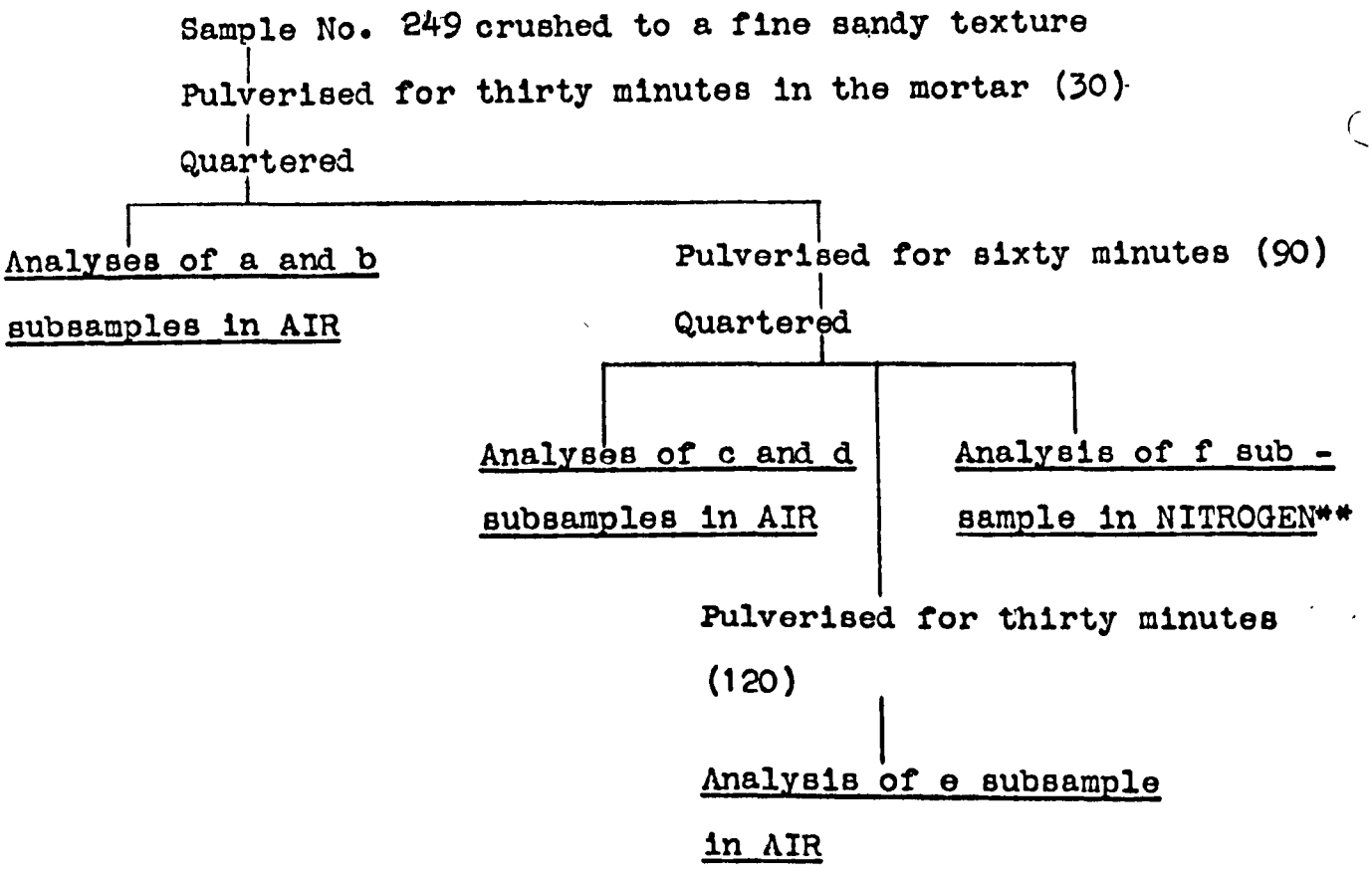
Pulverised by hand

Sieved through M100

56% Relative Humidity

Clay Fraction ready for Analysis

Figure 100. Pretreatment of Differential Thermal Specimens.



** This analysis is part of a separate test.

The bracketed numbers are total pulverisation time for the material concerned.

Figure 101. Rock Pulverisation Tests for Differential Thermal Specimen Particle Size - Flow Sheet.

On figure 102 it is seen that the curves of specimens a and b are not identical to each other indicating that the material was too coarse for good reproducibility. However the curves of specimens c, d, and e are for the purposes of this study identical and they show the presence of an exothermic effect between 350° and 450° C which is absent on curves a and b. This indicates that there is satisfactory reproducibility after 90 minutes of pulverisation and that no practical purposes are served by pulverising for 120 minutes (specimen e). N.B. The small sharp endothermic effect at 535° C has since been shown to be inherent in this apparatus (Chapter 26). The analysis of the sixth specimen f is illustrated but is considered in the later section on furnace atmospheres.

Particle Size Analyses of D.T. Specimens.

Certain of the powdered specimens were dispersed in calgon and analysed in the Sedimentation Balance to determine particle size characteristics; the results are shown in table 33 . It is seen that the mortar machine is unable to pulverise these rock and silt specimens down to clay size material: 76.5% of the rock and 82% of the silt remains larger than 0.002 mm after pulverising for 90 minutes. Thus there was no need to pulverise the silt material in this study.

The alteration of D.T. properties by the physical effects of pulverisation on the crystalline minerals are not considered here. The pulverising conditions of the rocks are, however, rigidly standardised with this in view.

Shape, Size, and Dilution of Specimens; Sensitivity of the Apparatus.

The purpose of this section is to discover the optimum

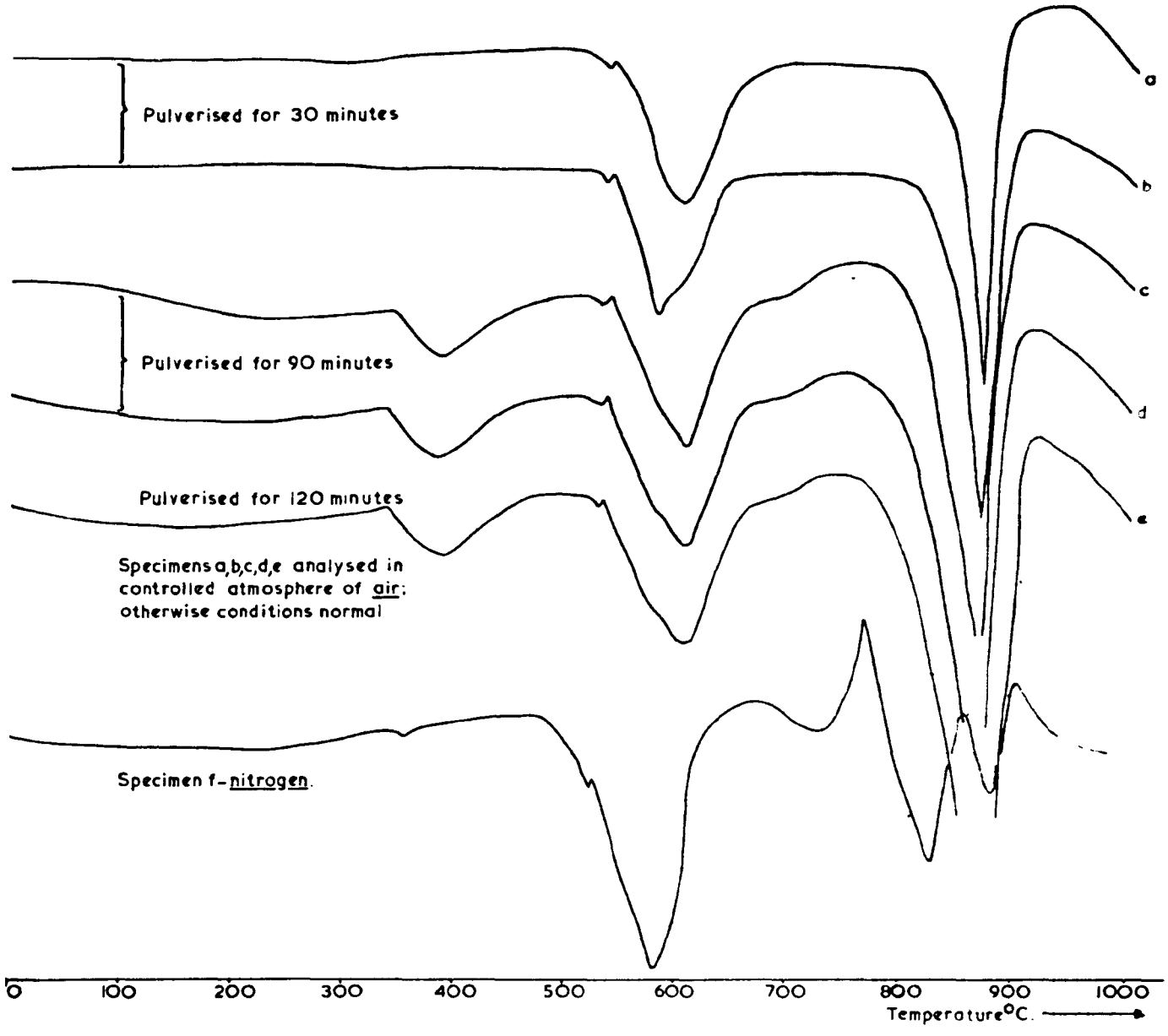


Figure 102. Pretreatment - Pulverisation. (Tuff Sample No. 249; flow sheet on figure 101)

Table 33. Particle Size Distribution of Differential Thermal Specimens.

Specimen Type	Sample No.	Sand Grade Percent	Silt Grade Percent	Clay Grade Percent
Rock, - pulverised for 1½ hrs.	249	0.5	76.5	23.0
Clay Fraction - Centrifuge	176	0.0	0.0	100.0
Clay Fraction - Settling Bottle	205	0.0	25.0	75.0
Silt Fraction - Centrifuge (unpulverised)	176	1.0	91.0	8.0
Silt Fraction - Settling Bottle (unpulverised)	205	0.0	87.0	13.0
Silt Fraction - Settling Bottle (pulverised)	205	0.0	82.0	18.0
Inert Material	Molochite	0.0	0.0	100.0

procedure after considering three ideal conditions:

a. The peaks are as distinct as possible.

b. The peaks never run off the chart.

c. Base line drift other than that caused by inher-
-ent apparatus factors (Chapter 26) is reduced to a minimum to facilitate measurement of peak areas. Mackenzie and Mitchell (1957) recommend that dilution of specimens with inert material is often adviseable in this respect because the thermal conductivity of the undiluted specimen may differ considerably from that of the inert. This gives rise to base line drift and weaker correlation between peak area, heat of reaction, and the quantity of reactant present. Dilution, however, brings the two thermal conductivities closer to each other; thus Sewell and Honeybourne (1957) recommend on theoretical grounds that dil-
-ution increases the accuracy of quantitative work. Dilution tests were thus performed to assess the importance of:

a. The reduction of base line drift.

b. The reduction in distinctiveness of the peaks as a result of dilution.

Both normal dilution by dry mixing and "sandwiching" the specim-
-en between two inert layers were tested. The following tests were performed, all in a controlled furnace atmosphere of air:

a. Quartz (α to β inversion at 570° C approx. - fig. 103)
Difference Recorder set at 5 - 0 - 5.

i. Sandwiching, results on table 34 a, graph of sample weight vs peak height on figure 103a.

ii. Complete Mixing, results on table 34 b, graph of sample weight vs peak height on figure 103b.

N.B. 0.450 gms quartz filled the crucible, specimens not diluted.

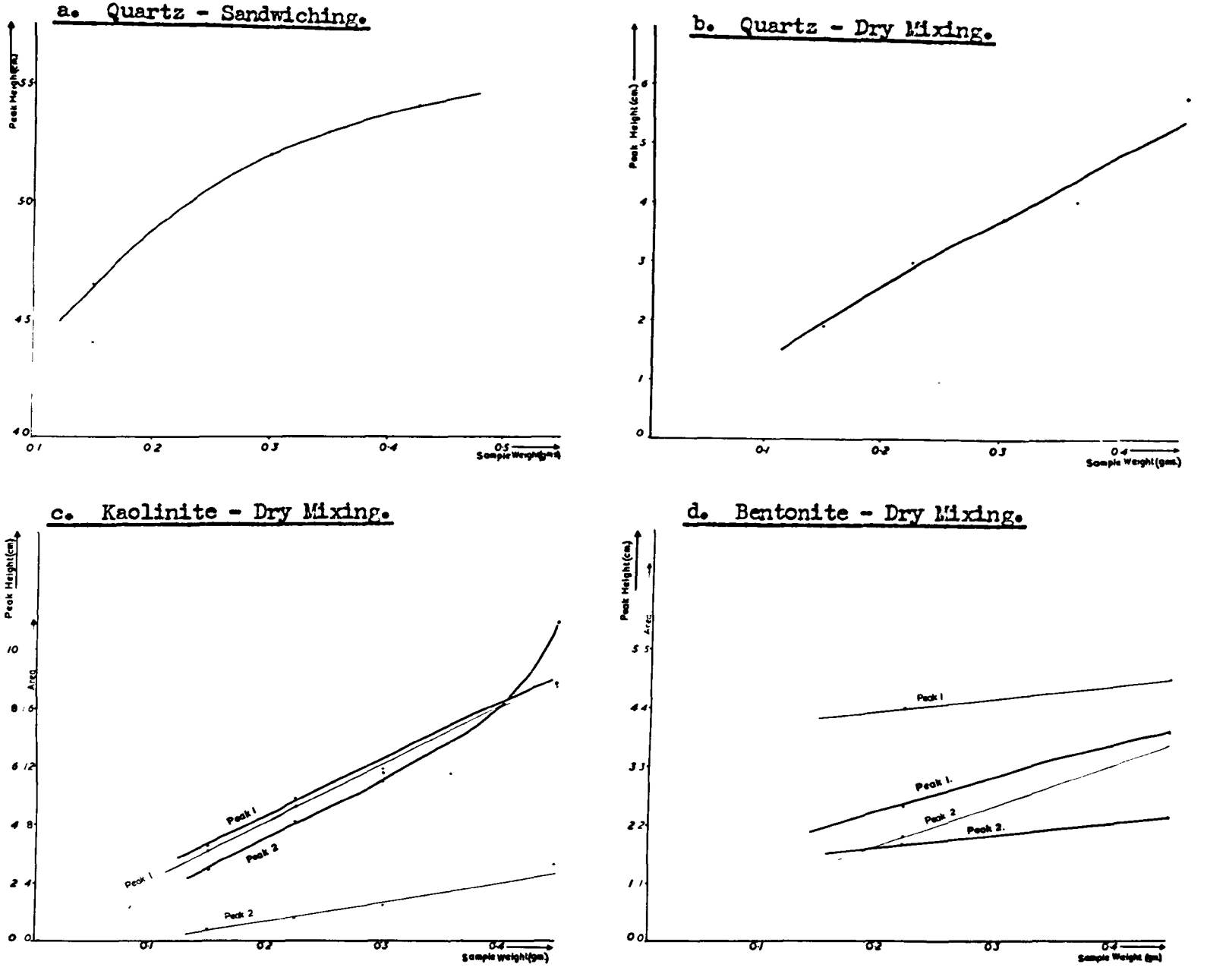


Figure 103. Thermogram Peak Heights and Areas - Sample Weights.

Table 34. Dilution Tests with Differential Thermal Specimens.

Mineral and Type of Dilution	Weight of Specimen (gms)	Peak Height (cms)		Peak Area (sq. cms)		Peak Temps. (°C)	
Quartz - Sandwiching	0.150	4.40				577	
	0.150	4.65				577	
	0.300	5.20				577	
	0.450	5.40				577	
Quartz - Complete Mixing	0.150	1.90				577	
	0.225	3.00				577	
	0.300	3.72				577	
	0.360	4.00				577	
	0.450	5.40				577	
Kaolinite - Complete Mixing	0.150	3.25	2.48	4.87	0.87	600	970
	0.225	4.90	4.10	8.57	1.64	600	970
	0.300	5.50	5.40	11.10	2.16	600	971
	0.360	7.10	5.70	14.2	3.50	604	975
	0.450	8.41	10.81	16.82	5.41	610	979
Bentonite - Complete Mixing	0.225	2.30	1.70	4.00	1.70	154	688
	0.450	3.60	2.10	4.50	3.67	157	719

b. Kaolinite, two peaks: 1. endothermic at about 600° C
2. exothermic at 1000° C.

Difference Recorder set at 20 - 0 - 20.

Results on table 34 c, graphs of sample weight vs peak heights and areas on figure 103c.

c. Bentonite, two peaks: 1. endothermic at about 150° C;
2. exothermic at 700° C.

Difference Recorder set at 20 - 0 - 20.

Results on table 34 d, graphs of sample weight vs peak heights and areas on figure 103d.

N.B. The method of measuring Peak Areas is shown on figure 104.

Conclusions.

a. Specimen Size: 0.200 gms. Tests showed that specimens larger than this of certain Windermere samples gave low temp-erature endothermic peaks which were off the charts (fig. 107a below) If necessary the recording pen could be loosened and moved to the left along the slidewire. This was not done for any of the routine analyses. The distinctiveness of the peaks is not effectively reduced for this size of specimen.

b. Dilution: "Semi Sandwiched". The weighed specimens were packed into the bottom of the crucible and inert packed in on top as shown in figure 105. The tests showed that base line drift is not markedly reduced by either method of dilution until the specimen is too small to give satisfactory peaks (fig. 103). The instrument drift (fig. 92 b)is generally predominant but the base line is also shifted after certain peaks (calcite peak on figs. 102 and 104). This shift is not reduced sufficiently to make dilution important.

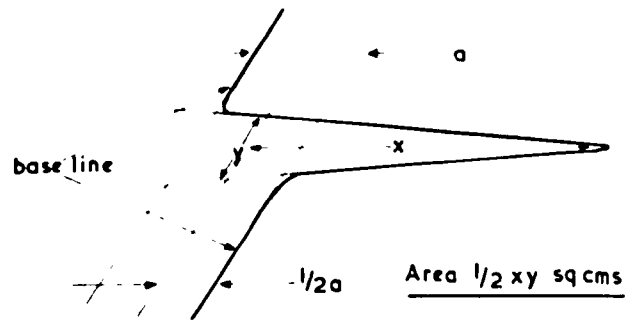
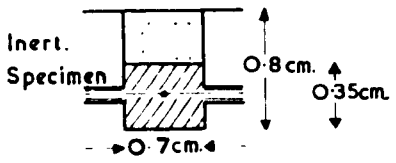


Figure 104. Measurement of Peak Areas.



Height/Diameter Ratio: 0·5

Figure 105. Crucible Packing.

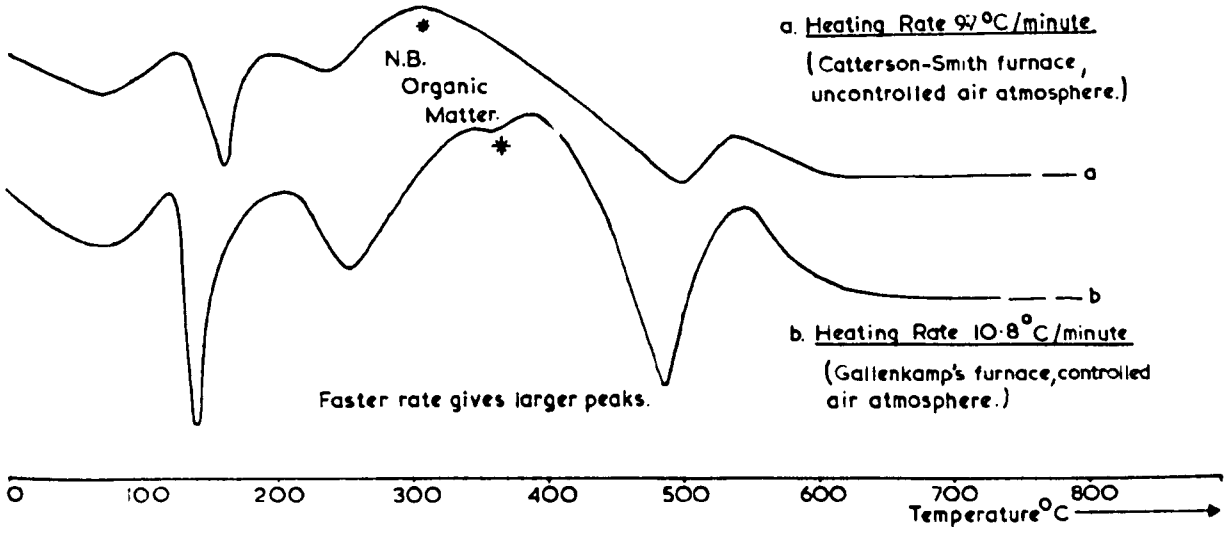
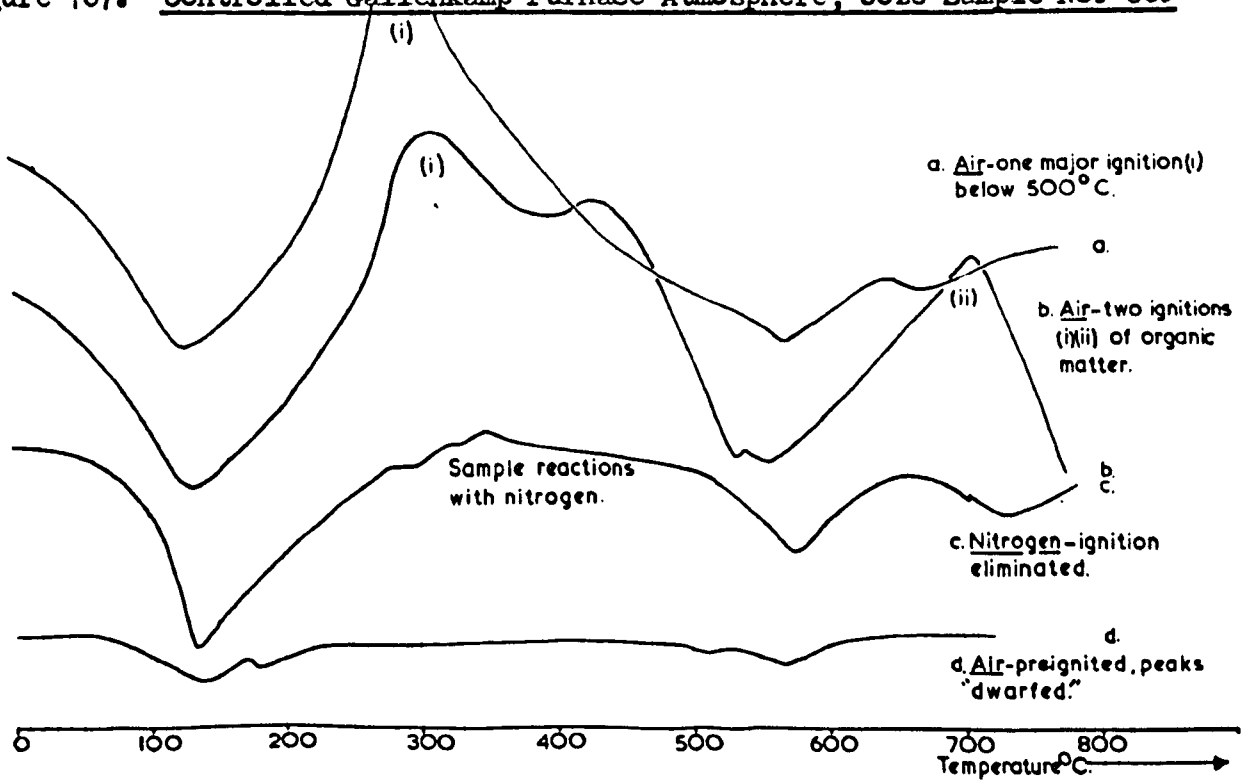


Figure 106. Effects of Heating Rate; Rusty Clay Sample No. 185.

Figure 107. Controlled Gallenkamp Furnace Atmosphere; Ooze Sample No. 60.



c. Shape of Specimen: Cylindrical, height/diameter ratio is 0.5. Sewell and Honeybourne (1957) have shown how peak area increases with decreasing height/diameter ratio.

d. Sensitivity of the Apparatus: This depends upon the size and shape of the crucibles, upon the method of packing and dilution, and upon the heating rate and temperature deflection sensitivity of the difference recorder. Mitchell (personal communication, 1962) suggests that apparatus sensitivity is best quoted as the peak height given by 0.150 gms quartz. This is 4.40 cms when the instrument is adjusted to 5 - 0 - 5 full scale deflection. This is referred to as a sensitivity of S.
The 20 - 0 - 20 adjustment gives a sensitivity of 1/4.S.
The 40 - 0 - 40 adjustment gives a sensitivity of 1/8.S.

Packing of the Crucibles.

The powders are packed firmly with a small flat ended glass rod of smaller diameter than the crucible. It is necessary to pack the specimen firmly into the sample crucible before packing it to the top with inert. Pretreatment ensures that there are no large aggregates to hinder uniform packing.

Position of the Temperature Thermocouple.

Ideally peak temperatures and other characteristics of the curves are taken from the specimen itself (Mackenzie, 1957). However in this apparatus the temperature thermocouple is in crucible no. 3 containing inert; corrections are not made for this deviation.

Heating Rate.

This method of mineral analysis is dynamic so that the specimen is submitted to steadily rising temperature and is

never in chemical or thermal equilibrium with the furnace con-
-ditions. Therefore the reaction velocity is important in assessing the heating rate. High velocity reactions give sharp and narrow peaks; lower velocity reactions give less distinct and broader peaks (Silfverberg, 1955). The ideal heating rate takes this into account; it is 10° C±1 per minute. Slower rates than this give rise to small broad peaks and faster rates to over-
-lapping of neighbouring peaks (Mackenzie and Mitchell, 1957). The effect on the curves of small differences of heating rate is considerable (fig. 106). Therefore the heating rate in the Gallenkamps' furnace with Block No. 2 as used in this work is reproducible (fig. 89 b). This system gives an average heating rate from room temperature to 1100° C of 10.8° C/minute. The difficulty of obtaining an identical heating rate in the Catterson-Smith furnace is one reason for not attempting to use it in this study, even for non organic material.

Furnace Atmosphere.

Both the type and the pressure of the furnace atmosphere are important because the thermal conductivity of the two packed specimens is largely dependant upon the gas filling the pore voids. It is, in fact, because of the high porosity of even a firmly packed powder and because of the similar gas filling this space in both crucibles that thermal conductivities are not sometimes very different giving rise to serious base line drift. Thus, when there is a reaction involving escape of gas from a specimen (for example carbon dioxide evolved from ignited organic matter and from decomposing calcite, dehydration, and dehydroxylation) the base line is likely to deviate while the new gas fills the voids. Therefore a controlled furnace atmosphere has been

recommended for all purposes by Sewell and Honeybourne (1957) so that the base line returns to near its original position and direction after removal of the new gas by the furnace flow. These base line effects are reproducible if the flow is the same and so they are an inherent D.T. property of the specimen.

Jonas and Grim (1957) recognise that furnace atmosphere control is a new and largely unexplored technique but claim that proper furnace control can give rise to the detection of peaks which would otherwise go unnoticed (a simple case is the supp--ression of the ignition of organic matter); and also to new data on the structure of clay minerals.

Organic Rich Material.

The organic matter ignites in an oxygen atmosphere but not in nitrogen. Sometimes it ignites rapidly at about 300° C, though with an uneven peak, and sometimes slowly giving two distinct exothermic reactions, one below 500° C and the other above 500° C (fig. 107a and b). The nature of these exothermic reactions is not investigated in this work though they have been used to determine the quantity and composition of the organic matter in the specimen (Silfverberg, 1955). A nitrogen furnace atmosphere suppresses ignition reactions (fig. 107c) but these curves are not likely to be the same as those obtained in an oxidising atmosphere if the discrete organic particles were not present (N.B. Hypothetical) for three reasons:

a. Organic matter may form molecular complexes with mineral matter (Greene-Kelly, 1957).

b. Mineral matter often has different properties in diff--erent atmospheres (see following section)

c. Base line effects are different.

N.B. The organic matter was removed by normal ignition in one case (fig. 107d); this eliminated the major exothermic effects but the mineral peaks that do occur are "dwarfed", except for quartz, compared with the same sample in nitrogen before it was ignited. In fact, this specimen was "semi-calcined" as expected.

Non Organic Material.

Mineral matter may have different thermal reactions in different atmospheres. Oxidation of certain minerals such as those containing ferrous iron (pyrite) or manganous manganese does not take place in nitrogen, so that if such a reaction does cause a peak in oxygen this is eliminated in nitrogen. Another aspect is the effect of furnace atmosphere on a reac-tion involving escape of gas from the specimen. On figure 102, compare c, d, and e analysed in air with f analysed in nitrogen. The endothermic effects between 350° C and 450° C has been eliminated in nitrogen though there is now a small peak at 350° C; whereas the endothermic and exothermic peaks between 700° C and 800° C are considerably more distinct in nitrogen than in air. The most important difference, however, is that the large calcite peak at 870° C in air has been reduced to two smaller effects at 830° and 880° C respectively in nitrogen. The dependance of this calcite peak system on furnace conditions is well known (Webb and Heystock, 1957).

Conclusions.

It is clear that furnace atmosphere conditions are of crucial significance in the production of a series of compar-ative D.T. curves. Thus the procedure in this respect has been rigidly standardised. This is also the main reason that the

Catterson-Smith furnace is not used for the analysis of Windermere material as well as the Gallenkamps' furnace. Thus for the comparative routine analyses the furnace atmosphere flow is reproduced at 200 ml per minute as suggested by Mitchell and Mackenzie (1959). It is always stated when a published curve or result in this work is obtained in an oxidising atmosphere.

Standardised Procedure.

a. Pretreatment. Separation of clay and silt fractions; suspensions dispersed with ammonia solution in distilled water. Clay is neutralised with 9N acetic acid, flocculated with magnes--ium chloride, decontaminated by centrifuging in absolute alcohol, dried at 50° C, and pulverised before brushing through Sieve Mesh 100. Silt is dried at 50° C and brushed through Sieve Mesh 240. Crushed Rocks are pulverised for 90 minutes. All Material is brought to 56% relative humidity.

b. Particle Size. Inert and clay material is smaller than 0.002 mm. Silt and crushed rocks are smaller than 0.064 mm. All aggregates are smaller than Sieve Mesh 100.

c. Size of Specimen. 0.200 gms.

d. Dilution. "Semi Sandwiched"; packed to the top with inert.

e. Sensitivity. S = 4.40 cms for 0.150 gms quartz; also 1/4.S and 1/8.S.

f. Packing. Firm and in two stages.

g. Shape of Packed Specimen. Cylindrical; height/diameter ratio is 0.5.

h. Position of Temperature Thermocouple. Inert, no correction.

i. Heating Rate. Average is 10.8° C/minute; reproducible.

j. Furnace Atmosphere. 200 ml nitrogen/minute unless other--wise stated.

Chapter 26. The Interpretation of Differential Thermal Curves or Thermograms.

Purpose.

Each mineral is represented on a thermogram by a peak or set of peaks (or other thermal effects) the interpret--ation of which requires some discussion. The methods by which the mineral composition of the samples analysed are derived from the thermograms are described in this chapter.

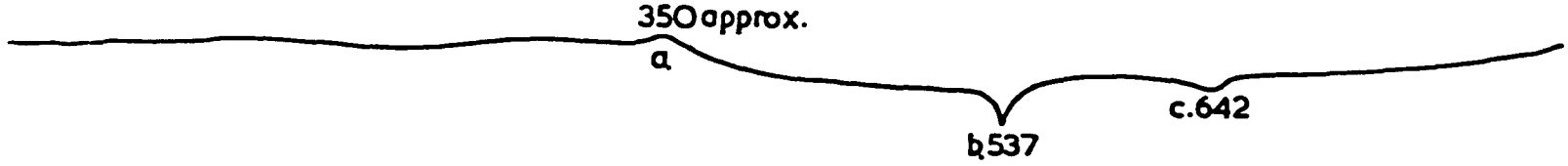
Base Line.

The instrument base line drift due to assymetry of the difference crucibles and thermocouple characteristics has already been discussed; it is assessed for each thermocouple pair and is accounted for in studying the curves. It is eliminated for purposes of drawing the curves in this chapter. Block No. 2, of nickel with quartz insulating tubes, has further effects on the instrument's base line; this is shown and explained in figure 108. These effects, likewise, are eliminated in subsequent diag--rams and interpretations.

Assymetry of the difference crucibles is accentuated in the initial stages of the heating cycle and may cause spurious effects just above room temperature. The first thermal effect considered here is, therefore, the major endothermic peak of dehydration, this always occurs above 100° C.

Windermere Material. (Table 35a)

Not all of the samples taken during this study were analysed by this method; those that were were specifically chosen for their geographical positions and/or their horizons in the stratigraphic column.



a. Curie Point of nickel, rapid change of conductivity-reversible.
(Sewell and Honeybourne 1957.)

b. $\alpha-\beta$ inversion of quartz insulating tubes-reversible.

c. Unknown cause-irreversible.

Figure 108. Instrument Base Line - Block No. 2 (exaggerated).

(Experiment carried out normally with inert in both crucibles.)

Table 35. List of Samples Analysed Qualitatively.

Sample categories found in table 5; locality nos. in brackets.

a. D.T. Analyses (silt and clay fractions; rocks were crushed).

Surface Ooze; PGa1: 4(S30), 7(S38), 8(S40); PGa2: 9(C1), 13(S15); PGa3: 18(S4), 21(S7), 24(S10), 25(S16), 27(S19), 29(S23); PGa4,5,6: 31(S43), 34(S46), 37(S49); PGb: 39(B25), 40(B26), 41(B32).

Gyttja (cores at C3 and C11 were examined in detail); PGd1: 68(C3), 76(C11), 81(S11), 82(S18), 86(S25), 87(S41); PGd2: 90(C3), 98(C11); PGd3: 104(C3), 112(C11); PGd4: 117(C3), 123(C11); two "scrape samples" of gyttja: 30MP(C7), 31MP(C7).

Late Glacial; LGa1: 145(C3), 148(C3), 156(C9), 157(C12),159(C12). LGa2: 167(C12); LGa3: 176(C11), 177(C12); and scrape samples: 32MP, 33MP, 34MP; LGb1i: 186(S27), 189(S35); LGb1ii: 197(B28), 200(B39), 205(S31); LGc1: 211(B4), 212(B12); LGd: 218(B9), 222(B24). N.B. Also PGe: 137, 138, 139; PGg: 142, 144.

Pink's Soils. (N.B. Key; Ahs: A-horizon soil; Bhs: B-horizon soil; bc: boulder clay; Cs: composite soil. Troutbeck Water-shed Area: TB; Hol Beck Watershed Area: HB; Stock Ghyll Watershed Area: SG. Watershed Areas also apply to the rocks.) 224(TB,bc), 225(TB,Cs), 226(SG,Cs), 227(TB,Ahs), 228(TB,Bhs), 229(SG,Ahs), 230(SG,bc), 231(TB, ?), 232(SG,Ahs), 233(SG,Ahs), 234(SG,Bhs), 235(SG,Bhs), 236(HB,Ahs), 237(HB,bc), 238(HB,Bhs), 239(TB,bc).

Pink's Rocks. (N.B. Key; tu: Borrowdale Volcanic tuff; la: lava; Si: Post Borrowdale Volcanic sedimentary rock.) 240(TB,tu), 241(SG,la), 242(TB,tu), 243(SG,tu), 244(SG,tu), 245(SG,tu), 246(SG,tu), 247(TB,la), 248(TB,tu), 249(TB,tu),

P.T.O.

Table 35a continued.

250(SG,tu), 251(TB,tu), 252(TB,tu), 253(TB,tu), 254(SG,tu), 255(SG,tu), 256(TB,tu), 257(SG,tu), 258(SG,tu), 259(SG,tu), 260(SG,la), 261(SG,tu), 262(TB, ?), 263(SG,tu), 264(SG,la), 265(HB,Si), 266(HB,Si), 267(HB,Si), 268(HB,Si), 269(HB,Si), 270(HB,Si), 271(HB,Si), 272(TB,Si).

b. X-ray Analyses (silt and clay fractions unless stated).
9, 13, 81, 176 (silt fraction only), 186; 228, 234, 236, 237, 238 (clay fractions only of these five soils); 241, 244, 248, 251, 252, 256.

c. Heavy Mineral Analyses (light fraction analysed where stated).
9, 11(S11), 12(S14), 13, 14(S18), 15(S21), 16(S22), 17(S25), 66(C1), 67(C2), 68(C3; light fraction also), 69(C4), 81, 82, 83(S21; light fraction also),84(S22), 86, 88(C1), 89(C2), 90, 91(C4), 97(C10), 98, 99(C12; light fraction also), 103(C1), 104, 105(C4), 111(C10), 112, 113(C12; light fraction also), 117, 123, 124(C12; light fraction also), 157, 158(C12; light fraction also), 159, 168(C12), 176, 177, 185(S26), 186, 187(S29), 188(S33), 189, 202(S27), 203(S28), 204(S30), 205, 206(S33), 237.

d. Chemical Analyses (silt and clay fractions unless stated; full sample is that before grading into sand, silt, and clay; M.J. Pink performed all these analyses, see text).
13, 34, 112; 30MP, 31MP (full samples also of these two scrape samples); 148, 167; 32MP, 33MP, 34MP, 186 (full samples also of these three scrape samples and no. 186); 205, 212, 237, 240 - 244, 246 - 252, 255, 256, 264 - 272.
N.B. Most sample descriptions for b, c, and d are found in a.

Major Constituents - Illite, Chlorite, and Amorphous Aluminosilicates.

Discussions of the Four Peaks.

Peak 1. The first major effect is endothermic, it represents the low temperature dehydration of some of the clay material (illite and amorphous aluminosilicates) in which sorbed molecular water is driven off. The peak occurs between 100° C and 135° C; when present it varies from "large" to "very small" and is always broad and rounded; the effect starts at 60° to 70° C and ends at 230° C. Hydration appears to be an important result of the decomposition of the parent rocks and drift, the signific--ance of peak 1 is therefore discussed at some length in Chapter 31. The effect is particularly susceptible to slight variations in the pretreatment techniques (fig. 99) but these have been rigidly standardised and the routine results appear to be accurate and reproducible in this respect.

Peak 2. The second major effect is also endothermic, it is very much more variable than peak 1. It represents either the dehydroxylation of illite (Deer, Howie, and Zussman, 1962, p.221) and/or the dehydration of the brucite layer of the chlor--ite structure (loc. cit., p.147). The peak may occur between 530° C and 615° C; it is always present and may vary from "very large" to "small"; it may be broad starting at 460° C and ending at 640° C or narrow starting at 490° C and ending at 585° C. These variables appear to be dependant not only on whether illite or chlorite is the dominant mineral but also on the chemical comp--osition. This applies particularly to the chlorites and is con--sidered at greater length in Chapter 28.

Peak 3. The third major effect is also endothermic, the

peak occurs between 715° C and 745° C. When present it varies from "very small" to "medium" and is generally rounded; it starts at about 670° C and ends at about 745° C.

Peak 4. The fourth major effect is exothermic, the peak occurs between 755° C and 775° C. When present it varies from "small" to "medium"; it is always narrow but may be either sharp or rounded.

There is little published material on D.T. analyses in nitrogen because this is a recent technique. Peaks 1 and 2 appear to be standard for chlorite and illite (and amorphous aluminosilicates) but peaks 3 and 4 are not. The published standards for these minerals obtained from analyses in oxygen show the presence of a pair of peaks, endothermic and exothermic respectively, at 850° C to 950° C and at 900° C to 1000° C (Suveri, 1950; Grim, 1953, pp. 238 - 241; Deer, Howie, and Zussman, 1962, pp. 147, 221, 222). In fact, these standards are similar to peaks 3 and 4 except that they occur between 100° and 150° higher. It is suggested here that the dynamic nitrogen atmosphere has brought about this reduction in peak temperature for these two peaks and that the minerals concerned are normal chlorites and illites. If this is the case peak 3 represents the disruption of the remaining illite structure (Deer, Howie, and Zussman, 1962 p.221) and/or the dehydration of the talc layers of the chlorite structure (loc. cit., p.147). Peak 4 represents the formation of spinel (loc. cit., p.222).

Examination of Peaks 3 and 4 in Oxygen.

It would have been desirable to produce evidence obtained from thermograms of chlorite and illite analysed in oxygen in support of the above hypotheses. Unfortunately this has been

found impossible for the following reasons:

a. The standard Fithian illite does not give important peaks 3 and 4 in either oxygen (fig. 109a) or ~~oxygen~~ nitrogen (fig. 109b) and so peak temperature changes cannot be detected. Also there is no available standard chlorite powder.

b. Illite dominant Post Glacial Windermere material cannot be analysed satisfactorily in oxygen because the ignition of the organic matter alters the entire thermogram above about 250°. Thus there is no valid comparison between this illite analysed in oxygen and then in nitrogen. Two Late Glacial clays with low organic contents appeared to be illite dominant (from their nitr--ogen thermograms). These, samples nos. 186 and 189, were anal--ysed in oxygen; peaks 3 and 4 were non existant now though peak 3 had been significant in nitrogen. This experiment was thus of little value.

c. Most chlorite dominant rocks from the area contain suff--icient calcite to alter completely the thermograms above 800°. Thus peaks 3 and 4, while occuring below this calcite effect in nitrogen, may be masked in oxygen. It is important to note, how--ever, that they do not occur at the usual nitrogen temperatures in oxygen (730° and 770°); this is shown on figure 102 a, b, c, d, and e) though it cannot be ascertained if and where they do occur on these thermograms. An attempt at this was made with samples nos. 241, 266, and 269 because these appeared to be chlorite dominant rocks without calcite (from the nitrogen thermograms). Again, however, peaks 3 and 4 were at the usual nitrogen temperatures, but non existant in oxygen.

It was concluded that the "oxygen temperatures" of peaks 3 and 4 of normal Windermere material cannot be detected. In this

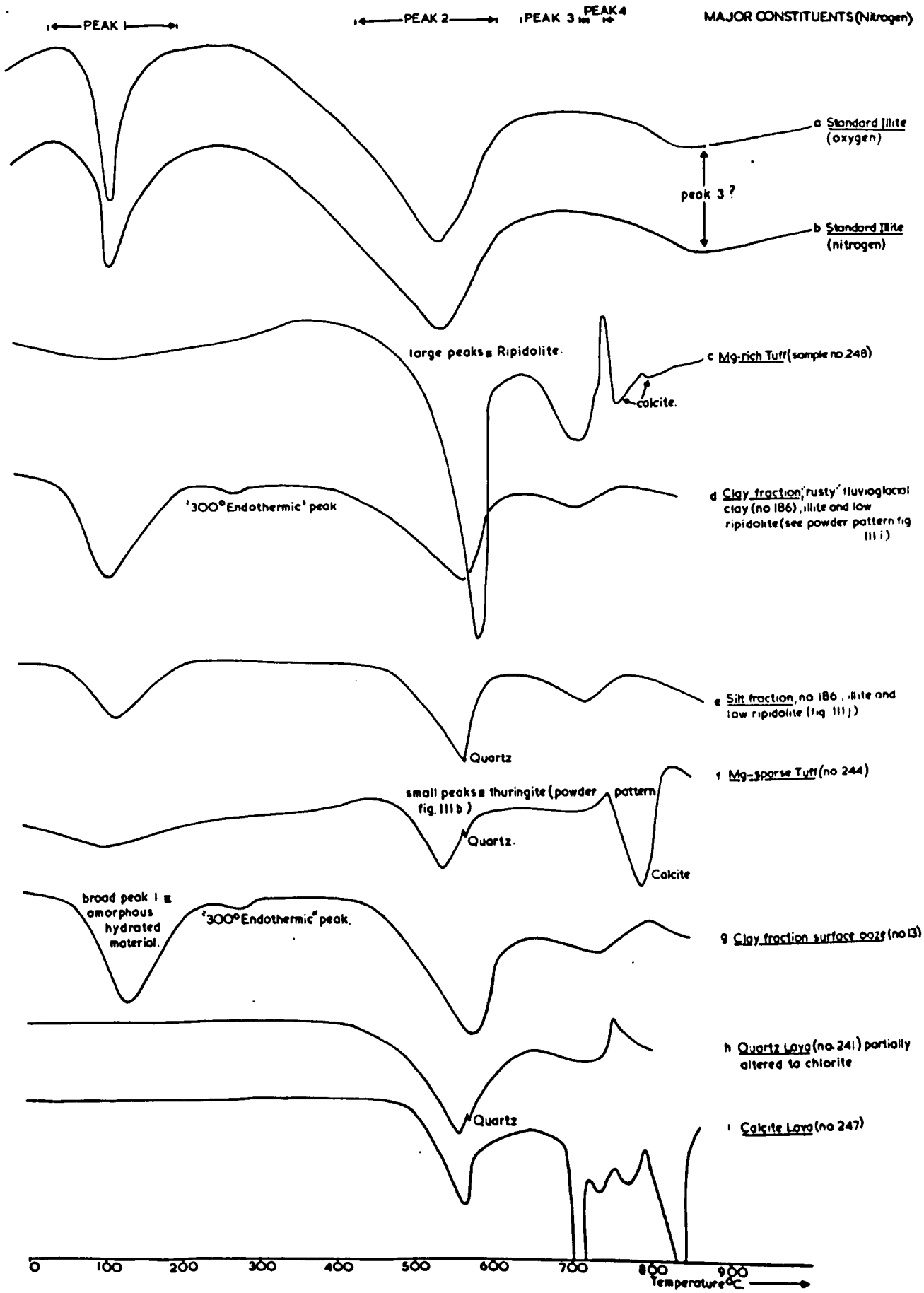


Figure 109. Thermograms to Illustrate Points Made in Chapter 26.

sense, the five test samples were necessarily abnormal and probably of little value for this reason. Only sample no. 249 (fig. 102), a normal chlorite dominant carbonate tuff, gives partial support to the hypothesis in that peaks 3 and 4 are not at the normal nitrogen temperatures when analysed in oxygen but are probably masked by the calcite effect.

Mitchell (personal communication, 1963) suggests that the temperatures at which peaks 3 and 4 occur may indicate the presence of a proportion of a serpentine mineral. There was no standard serpentine available but X-ray analyses (Chapter 27) do not support this.

Thus the problem involving peaks 3 and 4 which is im-portant for the interpretation of these thermograms cannot be said to be solved at this stage. However, the indications from the thermograms which are supported by X-ray results are that these peaks represent illite and chlorite and that they have been lowered in temperature due to the dynamic nitrogen atmosphere.

Identification of the Major Constituents.

(N.B. All illustrated thermograms in this section were obtained in nitrogen).

Chlorite. The members of this broad group are not normally termed clay minerals; they are regarded as low grade metamorphic minerals. Chlorite is common in the rocks in the Windermere area, noteably the tuffs in the Borrowdale Volcanic Series. It is also found in decreasing proportions in the Late Glacial and Post Glacial sediments in the basin. The D.T. properties of chlorite vary considerably depending largely on chemical composition (Deer, Howie, and Zussman, 1962, p.147). There are two

major endothermic effects and one exothermic effect corresponding to peaks 2, 3, and 4 respectively. The temperature of peak 2 varies from 550° to 620° whereas those of peaks 3 and 4 remain fairly constant at about 730° and 770° respectively. The relative heights of the three chlorite peaks remain approximately constant so that, when one is large, so are the other two and vice versa. Also it is found that the temperature of peak 2 is high when the three peak heights are large; these variations are discussed at greater length in Chapter 28. For purposes of interpreting the thermograms, however, the large peaks are taken to represent a high proportion of the magnesium rich chlorite ripidolite; sample no. 248 (fig. 109c) contains a high proportion of this mineral. The smaller peaks may either represent a lower proportion of ripidolite (sample no. 186, fig. 109d, e) or the ferric iron rich chlorite thuringite ; sample no. 244 (fig. 109f) contains this mineral. It is emphasised that these conclusions were not possible until the X-ray powder patterns and chemical data from the same material had been studied (Chapters 27, 28[1]), because neither standard chlorite powders nor published works on the thermal properties of the individual members of the group are available.

Illite. This group comprises the hydrated potassium rich clay micas with contracted lattices (Munoz et al, 1957).

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1. Chemical and thermal data on these chlorites show no clear distinction between the two end members; as MgO increases so do the peak areas. X-ray data, however, show that these are two distinct minerals. The implications of this anomaly are uncertain at this stage.

Sometimes K_2O is high and hydration low; this indicates low illite (Chapter 27). Illite used to be considered the typical clay mineral in certain freshwater environments but it is now known to be so common as to be termed "the quartz of the clays" (Weaver, 1958). Illite is found in low proportions in some rocks in the Windermere area, in some of the Late Glacial sediments, and especially in the more intensely decomposed Post Glacial sediments in the lake. The D.T. properties consist of three endothermic effects and one exothermic effect corresponding to peaks 1, 2, 3, and 4 respectively, a standard Fithian illite is shown in figure 109b. In Windermere material the peaks occur fairly constantly at about 120°, 550° - 580°, 720° - 745°, and 750° - 770°; peak 1 is generally large, peaks 2, 3, and 4 are generally medium. The clay and silt fractions of sample no. 186 (fig. 109d and e respectively) both contain about 50% illite. It can be seen that the dehydroxylation of Windermere illite (peak 2) sometimes takes place at a slightly higher temperature than the Fithian illite (580° compared with 560°) and that peaks 3 and 4 of the former are more distinct than those of the latter.

Amorphous Aluminosilicates. Mitchell in a personal communication (1963) suggests that the low temperature dehydrat-ion effect (peak 1) of the Post Glacial Windermere sediments is larger than can be accounted for by illite alone. It is likely that there is a proportion of amorphous hydrated aluminosilicates in many Windermere sediments giving this large dehydration effect (fig. 109g).

Organic Matter and Organic Complexes.

The organic content of Windermere material is obtained by simple ignition (Chapter 7) and is not considered here. There is, however, a possibility that some of the non vegeteble organic

matter may form complexes with mineral matter. Silfverberg (1955) pretreated D.T. specimens thermally and chemically in order to identify some of the organic matter present but the method was not successful with organic - mineral complexes and is not att--empted here. A nitrogen furnace atmosphere appeared to elimin--ate all organic reactions as well as ignition (fig. 107c); while in an oxygen furnace atmosphere the exothermic effects are so strong that they mask any special diagnostic D.T. properties that the complexes may exhibit. Thus it was not practicable here to study the nature of either the organic matter or the complex--es. Their effect is probably entirely one of dilution.

Inert Material.

It should be emphasised that mineral matter may be therm--ally inert in nitrogen over the temperature range used. If present this material would pass unidentified, and even undet--ected, because its only effect would be one of dilution of the thermal effects of the active material.

Borrowdale Volcanic Lava Flows.

The lavas are acid or intermediate and, if unaltered, would contain quartz, felspars, ferromagnesium minerals, and micas; they are not studied closely here. Sample no. 241 (fig. 109 h) is a quartz lava whose main constituent appears to be chloritic. This is likely to have been altered at some stage since deposition. Sample no. 247 (fig. 109 i) is a lava and its D.T. properties are not understood.

Identification of the Accessories.

Quartz. Some of the rocks, especially lavas, in the Windermere area, some soils, and some of the sediments, especial--ly their silt fractions, contain quartz. The D.T. properties of

this mineral have already been mentioned (Chapter 25); it is stable in all furnace conditions and is recognised by a sharp endothermic peak between 570° and 582° (fig. 109 f,h). The thermograms for pure white quartz are shown in Appendix No. 5. This peak represents the α to β inversion of quartz; in the pure mineral it occurs at 573.5° (Grimshaw and Roberts, 1957). The variations here are probably due to slight impurities; it was realised that they may have been a result of temperature measuring errors, but pure quartz consistently gives a peak in this apparatus at 577° (table 34) so this was probably not the case.

Some of the thermograms, particularly of silt fractions of unconsolidated material (fig. 109 e), exhibit a very sharp effect at about 580° (peak 2) compared with the more usual rounded form (fig. 109 d,g). This effect is thought to be due to the presence of quartz whose inversion in these exactly coincides with the expulsion of hydroxyl groups from the major constituent. The cooling curves, on which the α to β reaction gives an exothermic peak while the dehydroxylation is irreversible, support this.

Calcite. Some of the rocks, particularly those in the Borrowdale Volcanic Series, and some of the Late Glacial lacustrine facies in the basin contain calcite. The D.T. properties of this mineral have already been discussed (Chapter 25); the extent to which the size, shape, temperature, and number of the peaks is dependant on furnace conditions is reemphasised. The mineral is recognised by one or more sharp endothermic peaks between 780° and 900° (fig. 109 c, f). The thermograms for pure calcite are shown in Appendix No. 5. This peak system represents the evolution of carbon dioxide due to the decomposition of calcite as follows: $CaCO3 \longrightarrow CaO + CO2$. It takes place at higher temperat-

-ures in an oxygen atmosphere (fig. 102 a, b, c, d), its peak temperature is likely to have been lowered by the dynamic nitr--ogen atmosphere (Mitchell, personal communication, 1963).

Felspar. This is known to be present in many of the rocks especially lavas and also in some of the sediments (X-ray analyses, Chapter 27). However it has not been detected on the thermograms; it is probably inert over the range (McLaughlin, 1957).

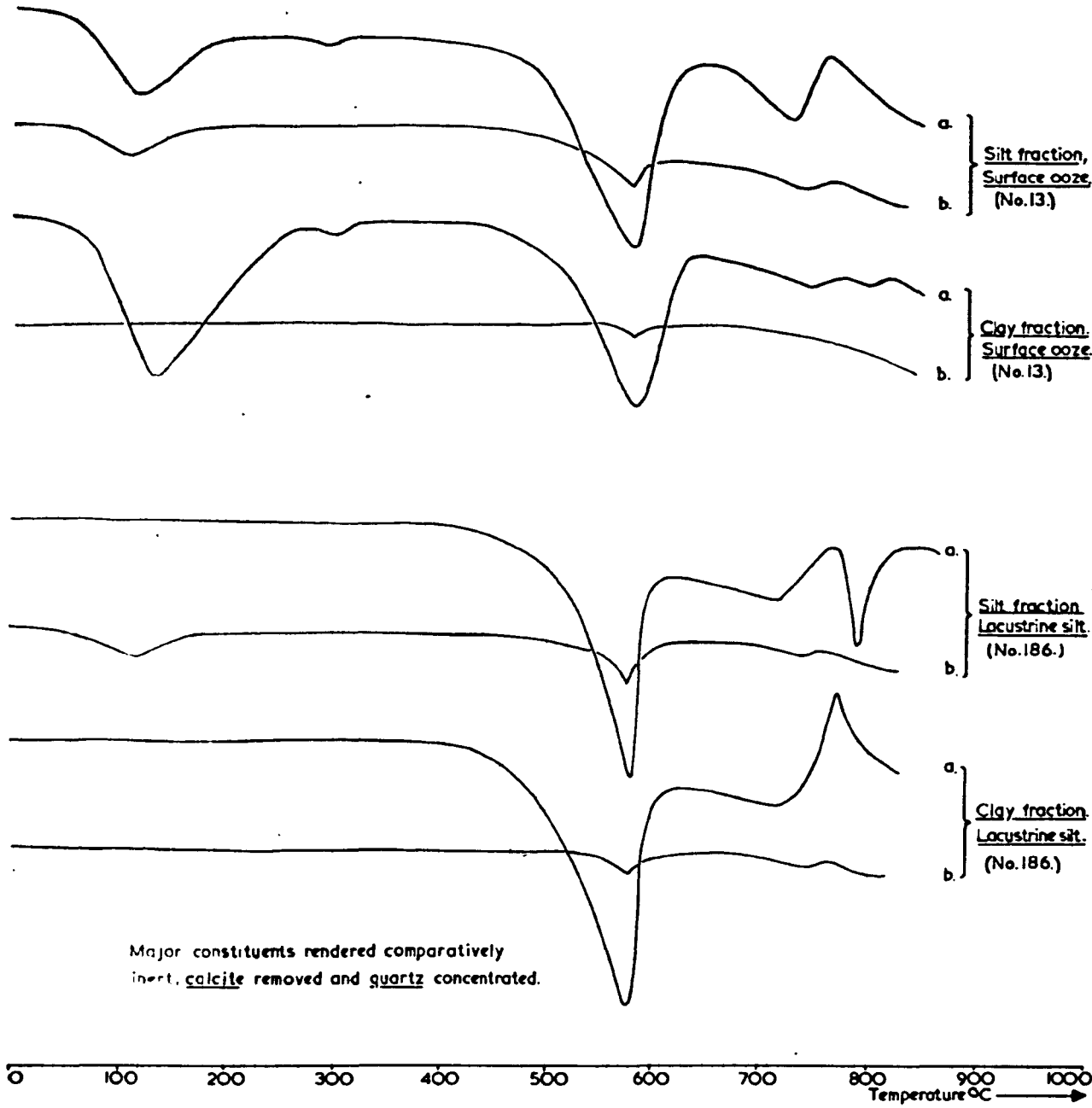
Pyrite. This is thought to be present in the Post Glacial sediments but it has not been detected because it does not react in a nitrogen atmosphere (McLaughlin, 1957) and it would be masked by the ignition of organic matter in an oxygen atmosphere.

Endothermic Peak at 280° to 320°.

This is present on the thermograms from some of all types of unconsolidated material (fig. 109 d, g) though not on those from the rocks. It may be a late stage of dehydration (Deer, Howie, and Zussman, 1962, p.221); the pure illite (no. 36) gives an equivalent at 309° (Appendix No. 5). It may be due to an accessory mineral though none was detected on the powder patterns.

Goethite. Mitchell in a personal communication (1963) suggests that the 300° peak may sometimes be due to this oxide of iron. Here the removal of iron from a number of specimens by gentle heating with 50% hydrochloric acid eliminated the peak. This test is not regarded as conclusive, however, because the thermograms were quite seriously altered in other respects by this acid treatment (fig. 110).

Vivianite. This mineral is white when fresh but rapidly oxidises on exposure to a vivid blue colour. It is often found



a. Before treatment.

b. After repeated treatment at 50°C; yellow colour removed.

Figure 110. Thermograms Showing The Effects of 50% HCl Treatment.

as small soft "nodules" in both Post Glacial and Late Glacial lake sediments in Windermere though it is unlikely to occur in soils and boulder clays. The 300° endothermic peak may represent vivianite though, if not, the mineral is either absent from or undetected in the D.T. specimens analysed. Sample no. 156, a pink lacustrine clay which was seen to be rich in vivianite (blue), gave a 300° endothermic peak though not as relatively large as may have been expected.

N.B. The standard thermograms for goethite and vivian-ite are shown in Appendix No. 5; they were obtained in oxygen. The problem of this peak has not been satisfactorily explained, it is referred to as the "300 endothermic peak".

The strong exothermic effect between 350° and 450° in the rock (tuff) sample no. 249 (fig. 102) is not understood, the analysis of this particular specimen was made in oxygen and the peak may represent the oxidation of iron ore accessories.

Quantitative Estimations of the Major Constituent.

Accurate quantitative work using thermograms is im-possible, it is even questionable that it can be done at all for the following reasons:

a. A peak may represent more than one mineral; for example, peaks 2, 3, and 4 in the Windermere thermograms may each be a result of two additive thermal effects, one in the chlorite pres-ent and the other in the illite. Peak 1 in Post Glacial mater-ial is a result of the loss of sorbed water, but it has been shown that some is lost from illite and some from amorphous hydr-ated aluminosilicates.

b. For minerals whose standards were obtained in this app-aratus the peak areas may represent total areas in the total

sample but it is emphasised that the standards only give general information about the thermal properties of that mineral. For example 100% Windermere illite may give different peak areas to 100% Fithian illite in the same way that their peak temperatures are slightly different. For minerals whose standards were not ob-tained in this apparatus there is no method of assessing a rel-ationship between peak areas and relative proportions; for example, chlorite and aluminosilicates.

c. Thermally inert material cannot be assessed; this may include material which was inert , specifically in nitrogen such as organic matter and organic - mineral complexes. In any case it dilutes the thermal effects present in the specimen.

d. Unidentified material cannot be assessed. Felspar, for example, may sometimes be present here in quite high proportions but either it is inert or otherwise unidentifiable and this can-not be determined.

In this work the proportionsof major constituents present in the samples are not derived from the thermograms; the X-ray powder patterns are used instead (Chapter 27).

Quantitative Estimation of the Accessories.

Quartz is determined by peak height assuming comp-lete mixing of the mineral within the specimen. Using the graph on figure 103b to give the weight of quartz present, the propor-tion is calculated of the total sample weight (0.200 gms).

Calcite. Chemical analyses of many of the samples containing calcite are available; they give the most accurate quantitative estimate. The relationship between CaO content and calcite peak area is discussed in Chapter 28 so that for samples where CaO was not available calcite is estimated from peak areas.

Other accessories are not determined quantitatively in this work.

While the proportions of the major constituents present in the samples are determined using the X-ray powder patterns as a guide, the quartz content is best determined from the thermo--grams and calcite from the chemical analyses where possible. The high degree of crystallinity of quartz and calcite appears to affect X-ray results (Chapter 21) whereas it probably does not affect the thermograms. Thus the quartz and to a certain extent calcite contents are markedly higher as determined by the X-ray method than the D.T. method. The latter data are taken as more significant.

Chapter 27. X-ray Diffraction Analyses.

This method of mineral analysis was used as a check for twenty selected specimens of clay fractions, of silt fractions, and of crushed rocks of which thermograms were available for com-parison; the sample nos. are listed in table 35b. They were subjected to X-ray diffraction using equipment in the Crystall-ography Dept., U. C. L., and the resulting data compared with D. T. data. Identical powders were used to prepare the specimens for both types of analysis (flow sheets, fig. 81).

The rotation powder method was used in all cases. The specimens were dried concentrated suspensions of powder in coll-odion acetate, tablet shaped, and approximately 0.1 x 0.1 x 1.0 mm. Copper radiation with a nickel filter (CuKα) at 30 kilo-volts and 15 milliamps was used; the exposure time was about 2½ hours. The camera was the standard Unicam, 3.0 cms radius, having a collimator 0.1 cms diameter. The films were developed immediately after exposure.

The mineral content of the specimens is determined from the powder photographs by calculating the three most important d-values and by comparing them with those of pure minerals. These latter were obtained as part of this work and also from standard tables. d-values are obtained as follows: 2x(mm), the diameter, is measured for three lines on each pattern. Corres-ponding values of θ are obtained from the "International Tables of Crystallography, Volume III", (table 2.4.2A, pp. 90 to 93). Bragg's Law is then applied : $n = 2d\sin\theta$. d-values, correspon-ding to the values of θ already determined, are obtained from the "Tables for Conversion of X-ray Diffraction Angles to Inter-planar Spacing (U. S. Dept. of Commerce, National Bureau of

Standards, Applied Mathematics Series 10)". Table 2 on p.21 of this publication gives the relevant data for copper Kα1 radiation with a wave length of 1.54050 Å. The relative intensities of the lines giving the measured d-values are also assessed.

X-ray Properties of the Minerals Present.

The American Society for Testing Materials (A.S.T.M. X-ray Powder Data File (Brindley, Editor, 1958) is used in conjunction with available standards. The chemical formula are taken from Deer, Howie, and Zussman (1962).

Chlorite. No standard powders are available for this group. The diagnostic d-values are listed in table 36 a and b.

a. Ripidolite. $[(Mg_{2.8}.Fe^{++}_{1.7}.Al_{1.3})(Si_{2.8}.Al_{1.2})O_{10}(OH)_8]$ This mineral is present in sample no. 248 (fig. 111a); also in the clay and silt fractions of sample no. 186 (fig. 111 i and j).

b. Thuringite. $[8FeO\ 4(Al,Fe^{+++})_2O_3.\ 6SiO_2.\ 9H_2O]$ A small proportion of this mineral is present in sample no. 244 (fig. 111b).

Illite. ($2K_2O.3MgO.Al_2O_3.24SiO_2.12H_2O$)

A standard Fithian illite is available (fig. 111c). The diagnostic and further useful d-values are listed in table 36c. The strongest line on this pattern (d = 3.34Å; 2x = 27.93) is identical to that for quartz (see below) and is not therefore diagnostic. This one and the four other lines listed are useful for assessing the proportion of illite in these samples (see below).

αQuartz. (SiO_2)

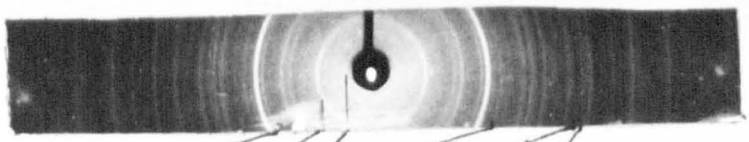
A standard pure white quartz is available (fig.111d). The diagnostic d-values and some further useful ones are listed

Table 36. X-ray Data.

N.B. The diagnostic lines, which are underlined in this table, are those three given in the A.S.T.M. File; the other lines given with some of the minerals were found useful in this work.

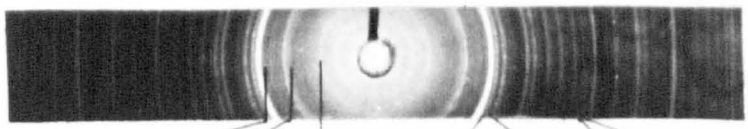
Mineral	'd - value' (A°)	2x (mm)	Intensity (/100)
Chlorite	7.07	13.09	100
a. Ripidolite	14.10	6.56	80
	3.54	26.33	50
b. Thuringite	6.90	13.43	100
	3.49	26.70	100
	4.63	20.08	80
c. Illite	10.00	9.23	100
	4.46	20.83	100
	2.56	36.67	100
	3.34	27.93	
	4.26	21.87	
	2.46	38.20	
	1.54	63.00	
	1.50	64.70	
d. Quartz	3.34	27.93	100
	4.26	21.87	35
	1.82	52.35	17
	2.46	38.20	
	1.54	63.00	
e. Calcite	3.04	30.75	100
	2.29	41.15	18
	2.10	45.07	18
	1.91	49.70	
	1.86	51.10	

Figure 111. X-ray Powder Patterns.



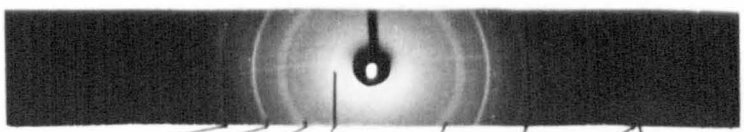
26·33, 13·0, 6·56, | 30·75, 49·7, 51·1. 2x (mm.)
(3·54)(7·07)(14·10) | (3·04)(1·91) (1·86) 'd-values'(A°)
Ripidolite | Calcite

a. Borrowdale Volcanic Tuff (no. 248).



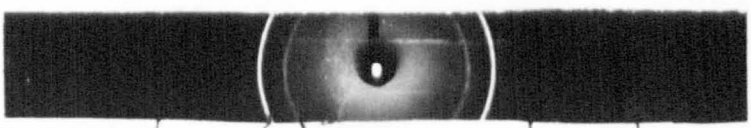
26·70, 20·08, 13·43, | 29·37, 30·75, 49·7, 51·1.
(3·49) (4·63)(6·90) | (3·18) (3·04)(1·91) (1·86)
Thuringite | Felspar | Calcite

b. Borrowdale Volcanic Tuff (no. 244).



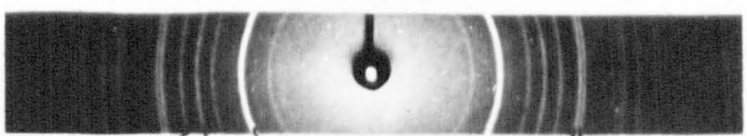
36·57, 27·93, 20·83, 9·23, 21·87, 38·20, 63·0, 64·7.
(2·56) (3·34) (4·46) (10·00) (4·26) (2·46) (1·54)(6·47)
Three diagnostic 'd-values'

c. Standard Fithian Illite.



52·35, 27·93, 21·87, 38·2, 63·0.
(1·82) (3·34) (4·26) (2·46) (1·54)

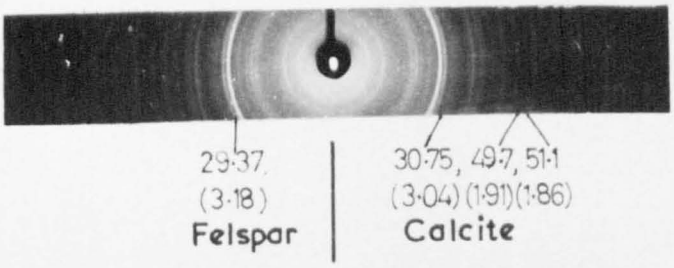
d. Standard Quartz.



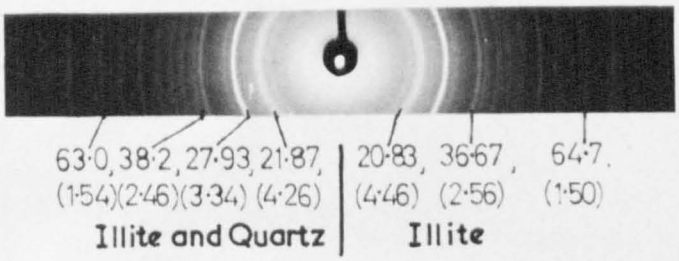
45·07, 41·15, 30·75, 4 9·7, 51·1.
(2·10) (2·29) (3·04) (1·91) (1·86)

e. Standard Calcite.

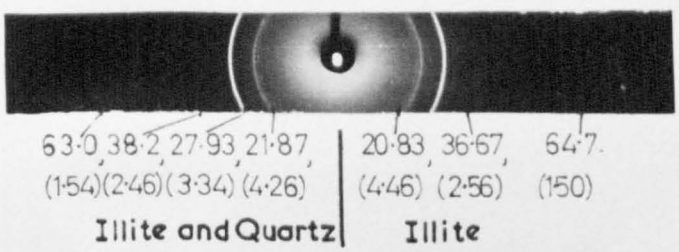
Figure 111 continued.



f. Borrowdale Volcanic Tuff (no.256)

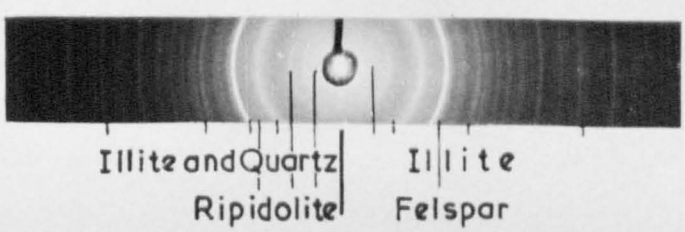


g. Artificial mixture of standards: 95% illite and 5% quartz.



h. Artificial mixture of standards: 50% illite and 50% quartz.

i. Clay fraction, "rusty" fluvioglacial clay (no.186). (see patterns a, f, and g.)



j. Silt fraction, "rusty" fluvioglacial clay (no.186) (cp. pattern i.)

95% illite and 5% quartz. (pattern g.)

Clay fraction, sample no.186. Illite/quartz ratio [100/trace]% (pattern i)

k. Illustration of the method for quick comparison and identification of powder patterns.

in table 36d.

Calcite. ($CaCO_3$)

A standard pure white calcite is available (fig. 111e). The diagnostic d-values and some further useful ones are listed in table 36e.

Felspar.

This mineral is difficult to define in these samples but a fairly strong line in some of the photos (d = 3.18Å; 2x = 29.37 mm) appears to correspond to orthoclase as given in the A.S.T.M. File. A standard pattern for felspar was not made. The mineral is thought to be in samples nos. 244 and 256 (figs. 111 b and f); and in the clay and silt fractions of sample no. 186 (figs. 111 i and j).

It is possible that certain other minerals may sometimes be present in small proportions, such as interlayered chlorite with montmorillonite or bentonite, and goethite. These are diff--icult to determine because their diagnostic lines nearly coin--cide with sets already present. It is also possible that amor--phous mineral matter (hydrated aluminosilicates for example) may be present in all types of Windermere material. This would be difficult to determine and its chief effect would be to "dilute" the patterns of the more highly crystalline material. In this respect quartz, which D.T analyses as well as chemical analyses and microscopic examinations (Pink, personal communication, 1963) indicate to be either sparse or absent in most material, gives fairly strong lines on the X-ray patterns. This is thought to be due to its higher state of crystallinity than the other minerals.

The organic matter in the Post Glacial sediments would have the effect of considerable dilution of the patterns.

Quantitative Estimations.

It is not possible to assess the proportions of minerals in these specimens accurately because of the unknown factors in--volved. These include amorphous and organic matter, degrees of crystallinity, and the possible presence of unidentified material. Each of the identified minerals is assessed as a proportion of the total identified material by considering the relative inten--sities of the lines on the powder photographs. This method seemed to be fairly satisfactory with respect to quartz, calcite, and illite whose pure patterns were obtained during this work (fig. 111 c, d, and e) because the relative intensities are known approximately for the exposure time (2½ hours). In this respect first consider calcite: the pattern for pure calcite (e) shows the "very strong" 3.04Å line (2x = 30.75 mm). The patterns b, a, and f, rock samples, show the same line though much weaker; its intensity relative to that for pure calcite gives the approx--imate calcite content. Thus sample 244 (b), with 5 to 6 percent calcite, gives a stronger line than either sample no. 248 (a) or 256 (f), with 2 to 3 and 1 to 2 percent respectively. These res--ults are supported by D.T. data. It should be noted also that the two lines (d = 1.91Å and 1.86Å; 2x = 49.7 and 51.1 mm res--pectively) are guides to determining the presence and propor--tion of calcite in these samples.

Now consider quartz and illite and the relative intens--ities of the following three pairs of neighbouring lines:

a. i. 2x = 63.0 mm (d = 1.54Å); illite and quartz.

ii. 2x = 64.7 mm (d = 1.50Å); illite only.

These lines have similar intensities when the mixture is of 95% illite and 5% quartz (fig. 111g).

b. .i.2x = 38.2 mm (d = 2.46Å); illite and quartz.

ii.2x = 36.7 mm (d = 2.56Å); illite only.

Line ii is more intense than line i in 95% illite and 5% quartz (fig. 111g). Vice versa in 50% of each (fig. 111h).

c. i.2x = 21.87 mm (d = 4.26Å); illite and quartz.

ii.2x = 20.83 mm (d = 4.46Å); illite only.

These lines have similar intensities in 95% illite and 5% quartz (fig. 111g).

By these three criteria, the approximate ratio of illite /quartz is assessed for each specimen. The 3.34Å line is "strong" on the pure illite pattern (c), "very strong" on the pure quartz pattern (d), and with an intensity between these two for mix--tures of (100% illite + quartz). Thus it is "strong"on g and "strong to very strong"on h. In quantitative work, having assess--ed the illite/quartz ratio from these pairs of lines, the int--ensity of the 3.34Å line is used to determine approximately the quantity of illite + quartz present and, ultimately, that of each of them individually.

The patterns for the clay and silt fractions of sample no. 186 (fig. 111 i and j) show the illite and quartz set of lines. Using the three line-pairs criteria above:

186 clay contains illite/quartz in proportions of 100/trace%

186 silt contains illite/quartz in proportions of 85/15 %.

Studying the 3.34Å line in these two patterns, it appears that 186 clay contains as little as 50% illite + quartz (or 50% illite and a trace of quartz) whereas 186 silt contains up to 80% illite + quartz (or 67% illite and 13% quartz). This is assuming degree

of crystallinity of Windermere material similar to that of the standard.

These methods cannot be used to determine the chlorite and felspar contents because standard powder photographs are not available. Here felspar is considered unimportant in this respect, but an estimate is made of the chlorite content by ass--uming that the 14.10Å line of ripidolite in sample no. 248 (a) and in the clay fraction of no. 186 (i); or the 3.49Å line of thuringite in no. 244 (b) represents 15% approximately of the chlorite mineral. This is the maximum chlorite content of these rocks estimated microscopically by Pink (personal communicat--ion, 1963). By this standard, no. 256 (f) and the silt of no. 186 (j) each contain 5% chlorite; the former is thuringite and the latter ripidolite.

The original negatives are always measured to avoid distortion due to printing. However, quick identifications and comparisons may be made with these negatives. Figure 111k shows the principle of this method (using positives for the illustrat--ion) in which the top half of figure 111g, the pattern for the artificial 95% illite and 5% quartz mixture, is superimposed on the bottom half of figure 111i, the clay fraction of no. 186 with approximately (100 /trace)% illite + quartz.

Chapter 28. Relating Mineralogical Analyses to some Preliminary Chemical Studies.

The chemical analyses of Windermere material, discussed below in relation to X-ray and D.T analyses, were all performed by Pink (personal communication, 1963). A thesis will appear under his authorship entitled "Geochemical Studies of the Source Rocks, Soils, and Sediments in the North Basin of Windermere". This will contain details of the chemical methods used. Therefore this aspect is joint work by Pink and the present author and the elements discussed here form only a preliminary study. Full analyses will be discussed by Pink later. All the sample nos. analysed here are listed in table 35d. The relevant data for this chapter are listed in table 37.

Major Constituent.

MgO Content of Rocks and Thermogram Characteristics.

X-ray analyses suggested that one of the chlorites, Mg rich ripidolite or Fe rich thuringite, is present in quite high proportions in many of the rocks. It was found that the former gave thermograms with a large peak 2 at a relatively high temperature as well as large peaks 3 and 4; and the latter vice versa. It has been mentioned that the ratio of the heights of peak2/peak3/peak4 remain fairly constant on the rocks which give all three. Three scatter diagrams were plotted (fig 112 a, b, c) and the chi-square test applied (Chapter 18). It was found that:

a. Height of peak 2 increases with that of peak 3 ($P<0.005$).
b. Height of peak 3 increases with that of peak 4 ($P<0.005$).
c. Height of peak 2 increases with that of peak 4 ($P<0.005$).

Thus there is a significant relationship between the

Table 37. Chemical Contents and Thermogram Characteristics.

a. Pink's Rock Samples.

Sample No.	Thermograms (present author) Peak Heights (cms) 1	2	3	Sum	Temp 2	Area, $CaCO_3$	Chemical Content (by Pink) MgO	CaO	FeO / Fe_2O_3	K_2O	P_2O_5
240	6.75	0.6	0.75	8.1	582	4.8	5.2	6.7	2.2	3.4	0.1
241	2.6	0.75	0.5	3.85	562	0.0	1.7	0.4	1.75	2.1	0.0
242	8.1	1.3	1.6	11.0	598	3.6	5.3	4.0	3.5	2.1	0.1
243	12.2	2.0	2.65	16.85	611	5.6	6.6	5.0	4.1	1.3	0.1
244	2.7	0.2	0.25	3.15	550	5.4	3.2	4.0	1.9	3.1	0.1
245	2.9	0.3	0.0	3.2	550	6.4	-	-	-	-	-
246	9.0	1.8	1.9	12.7	585	3.7	4.8	4.0	2.6	2.7	0.3
247	4.2	(fig.		1)	566	7.0	6.3	6.9	4.8	2.6	0.1
248	12.2	2.9	3.5	18.6	599	1.5	5.2	2.6	1.8	0.6	0.2
249	5.5	0.5	0.8	6.8	580	7.5	5.3	5.9	3.7	1.9	0.2
250	9.0	1.3	1.8	12.1	595	4.0	5.5	13.5	3.2	0.1	0.1
251	8.5	0.85	1.6	9.35	587	4.7	4.6	4.5	1.6	2.5	0.2
252	4.2	0.4	0.7	5.3	570	3.4	3.4	3.4	1.2	3.1	0.1
253	5.1	0.5	0.4	6.0	574	1.7	-	-	-	-	-
254	10.4	1.1	2.5	14.0	597	15.3	-	-	-	-	-
255	8.6	1.3	1.5	11.4	592	2.4	3.9	2.7	3.2	2.4	0.2
256	2.0	0.85	0.75	3.6	565	1.4	2.5	2.3	1.5	4.1	0.3
257	7.5	0.8	1.1	9.4	588	9.0	-	-	-	-	-
258	10.2	1.05	2.3	13.55	607	27.0	-	-	-	-	-
259	9.2	1.1	1.6	11.9	590	7.2	-	-	-	-	-
260	7.7	0.9	3.1	11.7	586	5.2	-	-	-	-	-
261	8.3	0.9	3.3	12.5	597	27.0	-	-	-	-	-
262	0.9	0.6	0.3	1.8	540	0.0	-	-	-	-	-
263	9.2	1.0	2.6	12.8	594	3.4	-	-	-	-	-
264	4.8	1.0	3.1	8.9	582	6.7	2.6	6.7	2.0	2.7	0.3

Table 37.

a. Pink's Rock Samples continued.

Sample No.	Thermograms (present author) Peak Heights (cms) 1	2	3	Sum	Temp 2	Area, CaCO3	Chemical Content (by Pink) MgO	CaO	FeO / Fe2O3	K2O	P2O5
265	-	-	-	-	-	0.0	0.6	0.1	0.4	4.1	0.0
266	5.4	1.3	3.2	9.9	572	0.0	2.2	0.9	2.4	2.0	0.2
267	2.9	0.5	0.6	4.0	548	1.8	1.9	2.3	10.0	2.6	0.2
268	4.3	0.3	0.5	5.1	578	0.85	2.7	2.6	2.6	5.0	0.1
269	3.6	0.5	0.7	4.8	575	0.0	3.5	0.9	2.2	4.0	0.1
270	3.1	0.6	0.3	4.0	582	7.5	4.3	5.5	1.5	3.1	0.1
271	4.2	(like fig. 1)			588	3.2	4.1	5.1	1.2	3.0	0.1
272	3.9	0.75	0.5	5.15	580	0.2	2.8	1.9	3.2	2.4	0.1

b. Sediment Samples - Chemical Content only (by Pink).

Sample No.	Facies	Full K2O	Full P2O5	Silt K2O	Silt P2O5	Clay K2O	Clay P2O5
13	Surface Ooze	-	-	2.6	0.2	3.0	0.85
34		-	-	2.6	0.4	3.25	0.6
112	Gyttja	-	-	2.7	0.3	4.4	0.2
30MP		2.95	0.5	3.1	0.2	3.2	0.45
31MP		2.8	0.6	2.6	0.3	2.2	0.5
148	Late Glacial Lacustrine Material	-	-	2.6	0.3	5.2	0.2
167		-	-	1.9	0.3	4.1	0.2
32MP		4.4	0.2	-	-	-	-
33MP		3.6	0.2	2.7	0.3	5.7	0.2
34MP		2.5	0.2	1.5	0.3	2.1	0.2
186	Late Glacial Fluvioglacial Clays	2.0	0.2	1.85	0.15	2.55	0.2
205		-	-	2.25	0.2	3.8	0.2
212		-	-	2.1	0.1	2.9	0.4
237	Boulder Clay (soil)	-	-	2.5	0.4	3.0	0.2

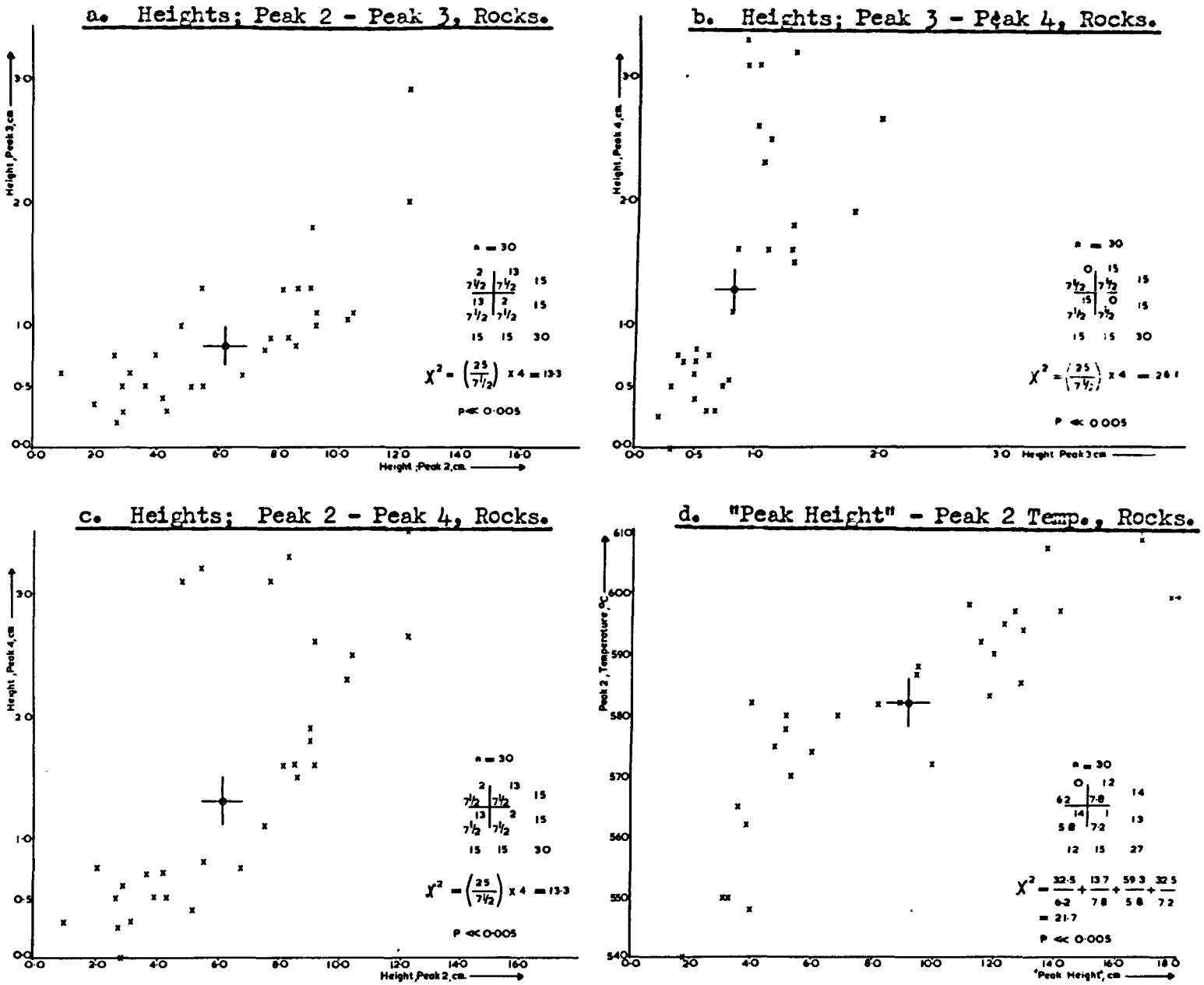
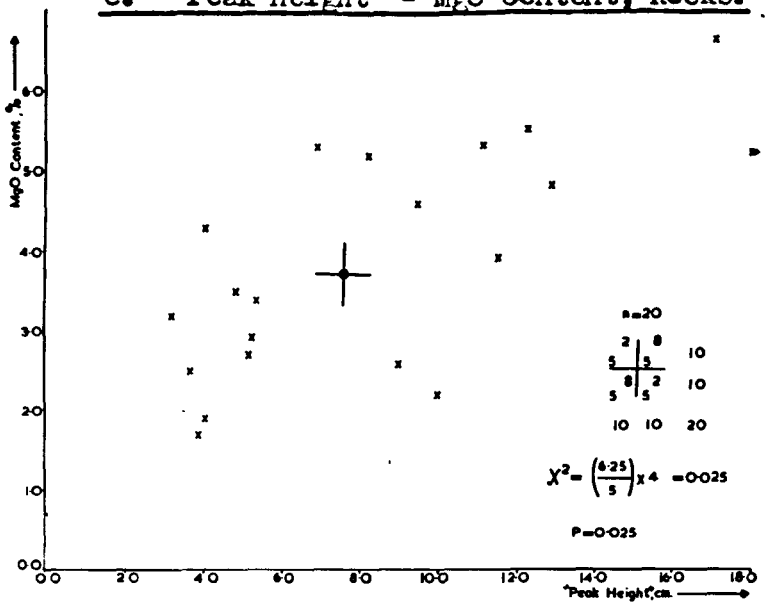
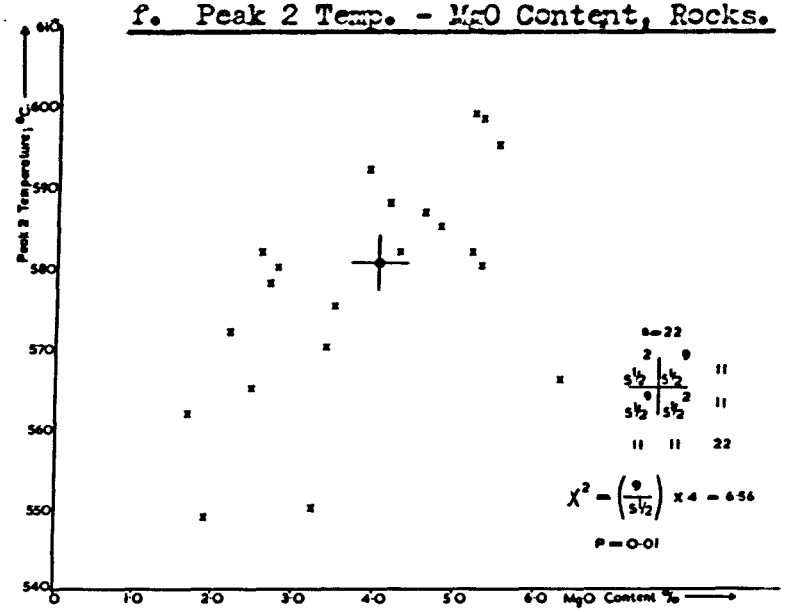


Figure 112. Thermal and Chemical Relationships; Chi Square Probability Tests.

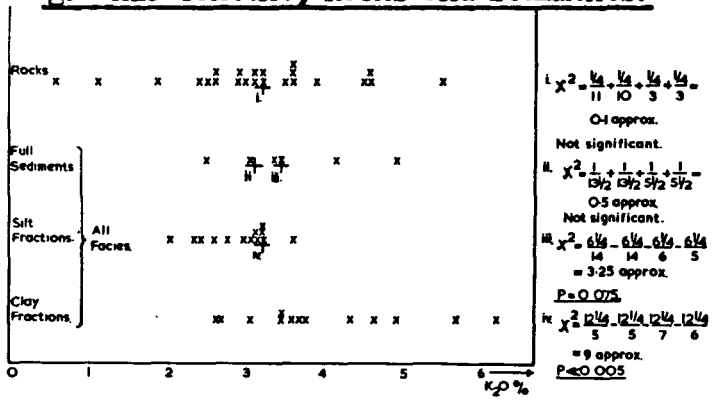
e. "Peak Height" - MgO Content, Rocks.



f. Peak 2 Temp. - MgO Content, Rocks.



g. K2O Content, Rocks and Sediments.



i Rocks vs Full Sediments. (n=29)

12 (11)	9 (10)	21
2 (3)	4 (3)	6
14	13	27

ii Rocks+Full Sediments vs Silt Fraction (n=42)

12 (13½)	15 (13½)	27
7 (5½)	4 (5½)	11
19	19	38

iii Rocks+Full Sediments vs Clay Fraction. (n=42)

17 (14)	11 (14)	28
3 (6)	8 (5)	11
20	19	39

iv Clay Fraction vs Silt Fraction. (n=26)

9 (5)	1 (5)	10
3 (7)	10 (6)	13
12	11	23

h. Calcite Peak Area - CaO Content.

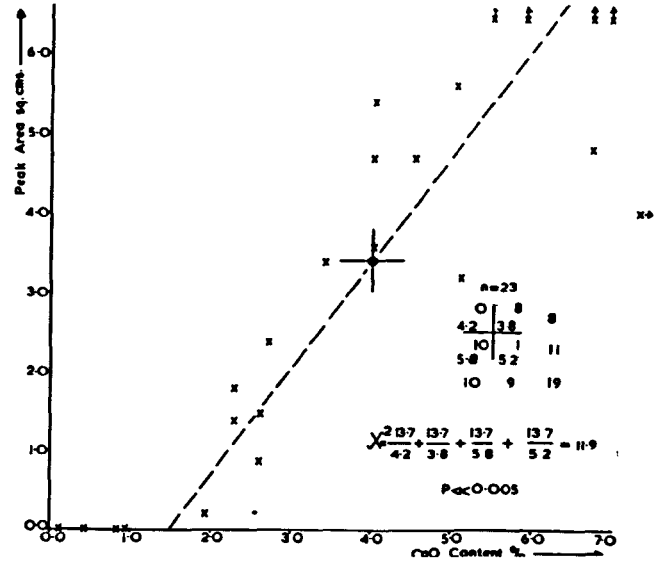


Figure 112 continued.

peak heights in the rock samples. The sum of these heights was taken as the value to represent the property termed here "peak height of the major constituent". This was now found to in-crease significantly with the temperature of peak 2 (fig. 112d; $P < 0.005$). The temperatures of peaks 3 and 4 showed no clear relationships to other thermogram characteristics.

Both peak height and temperature were found to increase significantly with MgO content (fig. 112e, f; $P < 0.025$ and 0.01 respectively). These results support those from X-ray analyses and both make for easier interpretations of the thermograms. However, unlike the X-ray method, the chemical and D.T. analyses do not appear to distinguish betweem thuringite and ripidolite. Instead there seems to be a gradation of rock contents from high MgO, giving large peaks and a high peak 2 temperature, to low MgO, giving small peaks and a low peak 2 temperature. The former contains relatively high ripidolite but whether the latter contains low ripidolite and/or thuringite cannot be assessed at this stage without the aid of X-ray powder patterns. Further work is to be done in this respect obtaining many more powder patterns and testing the results with those plotted on figure 112 e and f).

The scatter diagrams indicate clearly that, though the above relationships are significant to the 5% probability crit-erion, they are not simple relationships. A combination of physical and chemical factors affect the thermograms and it has merely been shown here that MgO content is probably one of them. The ratio FeO/Fe2O3 showed no apparent relationships to the thermograms. MgO is effective probably because of its high ionic radius. In contrast to this conclusion, Deer, Howie, and

Zussman (1962, p.147) say that the thermal data of chlorite is largely dependant upon Fe^{++} content.

K20 Content of Rocks and Sediments. (Table 37 a and b)

X-ray analyses indicate that illite is present in comp--aratively high proportions in the Post Glacial lake sediments, particularly clay fractions, and in lower proportions in Late Glacial sediments and rocks. Thermograms support this in that they indicate the presence of a high proportion of hydrated mater--ial in Post Glacial sediments (particularly clay fractions) and a lower proportion in the rest. An examination of the K20 cont--ent of Windermere material is shown in figure 112g which comp--ares rocks with full sediments (sand + silt + clay), silt frac--tions, and clay fractions. The last three categories include all sediment facies and show several interesting features:

a. The rocks contain a high proportion of K20 indicating that the felspar is orthoclase or microcline (or sericite where this has been decomposed). Plagioclase and its derivatives are probably less common because the CaO content is generally taken up with calcite (see below). Grim (1958, p.52) claims that "degraded" chlorites also contain K20.

b. It is impossible to distinguish statistically ($X^2 = 0.1$) between the K20 content of the rocks and that of the full sedim--ents though only six of the latter data were available here. This appears to indicate that K20 tended not to be carried off in solution.

c. It is impossible to distinguish statistically ($X^2 = 0.5$) between the K20 content of the rocks plus the full sediments and that of the silt fractions of the sediments. This appears to indicate that the silt fractions were equivalent to the rocks and

may have been unaltered rock fragments. It is possible, however, that silt fractions really contain less K20 than the rocks but that there was insufficient data to support this. In this case a certain amount of K20 may have been leached out of the small rock fragments before deposition, and concentrated in the clay fractions (see below)

d. The fact that K20 is concentrated in the clay fractions is well supported statistically (iii and iv; P = 0.075, not quite conclusive; and 0.005 respectively). This, in turn, sup--ports the postulated increase of illite (K rich hydrated mica) content of the clay fractions. In contrast to the D.T. and X-ray analyses in this respect, however, there appeared to be no distinction between Late Glacial and Post Glacial sediments. Thus while the hydration, and therefore the illite content, of the Late Glacial clay fractions is considerably lower than that of the Post Glacial clay fractions, the K20 content apparently shows no significant difference. It is tentatively concluded that K20 occurs in the non hydrated micas such as sericite and rock fragments (felspar and "degraded" chlorite, see above) in the Late Glacial rock flour.

H20 Content.

This would include molecular water (see peak 1) and hydroxyl groups (see peak 2). This important aspect was not considered here because of the difficulties encountered in meas--uring the molecular water of organic rich material quantitat--ively. Hydration of the major constituent appears to be an important aspect of Post Glacial weathering and it would have been of considerable interest to compare chemical data in this

respect with variations in the low temperature peak of dehydra-
-tion on the thermograms.

Alteration of the Major Constituent.

The availability of K2O and MgO is an important factor in determining how far chlorites and micas may be altered by chemical decomposition (Grim, 1958, p.52). Both these constit-
-uents are present in the majority of the rocks, MgO in ripidol-
-ite, K2O in felspar and its derivatives and illite (present according to X-ray analyses) and possibly "degraded" chlorite as well. Thus decomposition is promoted and a general simplified process may be as follows:

Rocks (hydration and decomposition)		Clay fractions
Chlorite	⟶	Illite
Orthoclase, sericite	⟶	K2O rich micas
Illite	⟶	Strongly hydrated (illite and amorphous aluminosilicates

CaO Content and Calcite Peak Area. (Rocks, table 37a)

The CaO and CO2 contents of the rocks are generally within 0.5% of each other and are taken here to be proportional to the calcite content (approximately). A scatter diagram (fig. 112h) was plotted of CaO content against the peak area of the calcite peak system on the thermograms (endothermic between 780° and 900° C). Generally there was one peak only but in cases where there were two the sum of their areas was plotted. It was found that peak area increased as CaO increased ($P < 0.005$). The relationship did not appear to be simple but this may be due to slight variations of furnace conditions giving spurious peak areas; and also to inaccuracies in the measurement of peak areas.

In fact it is possible that the relationship is simpler than this and that it would have been seen to be so if peak areas had been exactly reproducible. There are no observed calcite peaks from samples with less than 1% CaO. A straight line was drawn arbitrarily from the coordinate, CaO 1.5, peak area 0.0, through the double median. This is taken as representing this simple relationship. Calcite contents are determined from peak areas by reading the CaO content off the graph and multiplying by 1.79 (calculated from molecular weights).

SiO2 and Quartz.

The relationships here are obscure and quartz is found in some samples with as low as 50% silica; they are not considered here. As a general rule, however, relatively large quartz peaks on the thermograms are given by samples with more than 65% SiO2.

P2O5 and Vivianite. (Rocks and sediments, table 37)

Taylor (1949) has studied the phosphorus content of the Windermere sediments and its affect on the breakdown of organic matter, particularly as promoted by bacterial activity. It is found in higher proportions in the lake sediments than in the rocks (table 37) and occurs in some samples as vivianite. This mineral is probably formed in isolated pockets in the lake where conditions (pH, algal) are suitable both locally and temp--orarily. Vivianite was neither detected on the X-ray powder patterns nor confirmed on the thermograms. This localised conc--entration of phosphorus in vivianite manifests itself in two noteable ways: Its occasional appearance in kernels of hazel nuts; the occurence of a few lake sediments with exceptionally

high P205 contents (clay fraction, no. 13; table 37b).

Organic Matter.

CO2 in calcite bearing samples is largely accounted for; that in the organic rich sediments was not determined as the samples were necessarily ignited prior to analysis. Gorham (1960) has examined the relations between carbon and sulphur in organic Windermere sediments.

Chemical Content and Shape of Thermograms.

A further aspect of the work which has not proceeded far enough at this stage to advance any hypotheses involves the poss-ibility that the detailed shape of the thermograms (including peak heights, areas, widths, temperatures, and possibly base line drift) may be related to the comprehensive chemical content, within the framework of the observed mineral composition. It was thus noticed that the thermograms, from lake sediments part-icularly, were fairly constant in shape for one facies; also that each facies varied from the rest sufficiently for that shape to be diagnostic. These shapes were used to define part-icle populations. In several cases the observed mineral comp-osition could not be differentiated from one shape to another but the chemical analyses showed differences in detail which probably gave rise to the thermogram variations. Several exam-ples of this are shown in figure 113. The chemical contents are not given but it is hoped that further work will enable the therm-ogram variations to be classified chemically so that the comp-aratively rapid D.T. method may allow detailed identifications and comparisons of the material. The process of discovering the physico-chemical nature of the variations will be more complex.

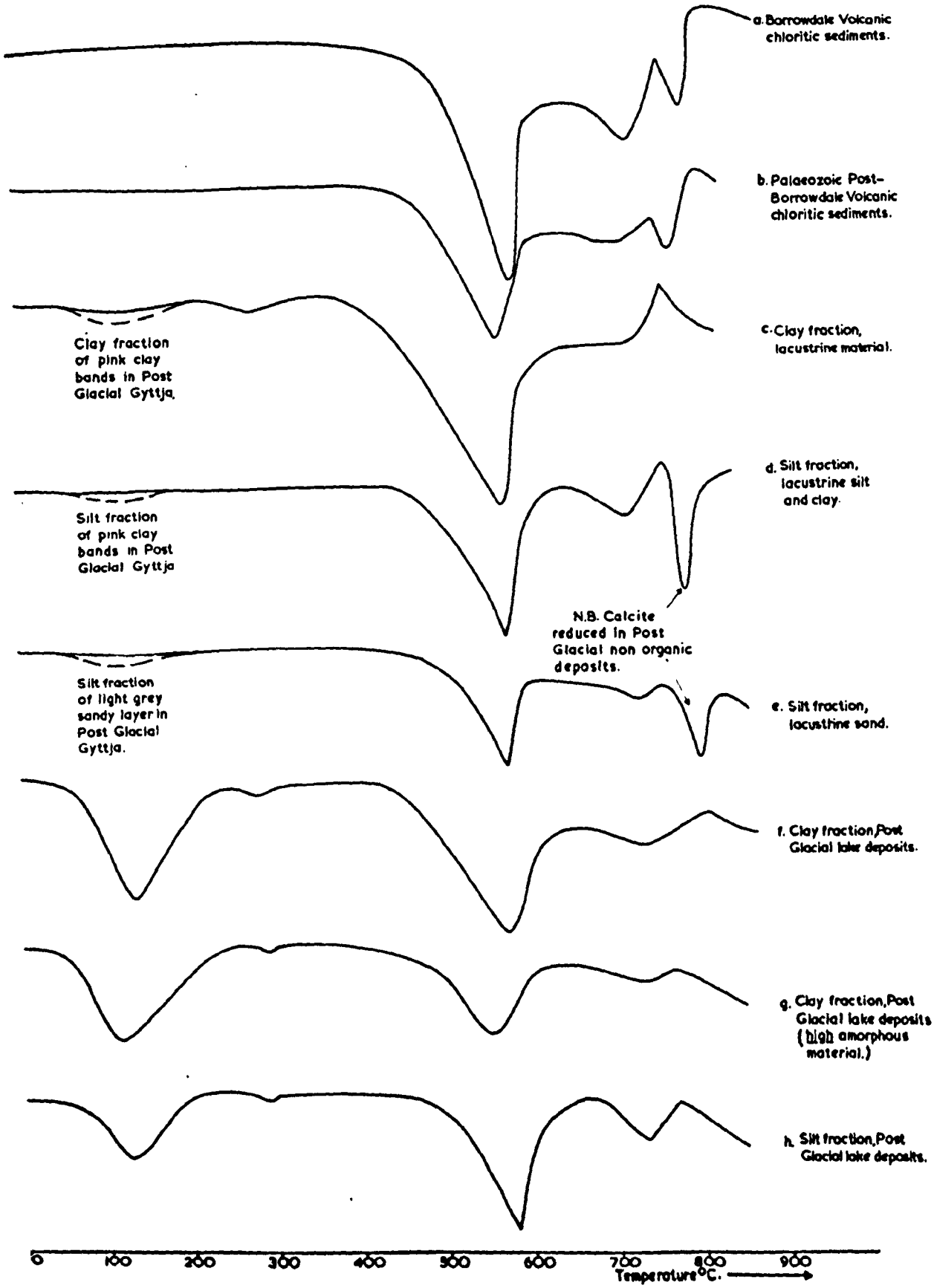


Figure 113. Typical Thermogram Shapes and Mineral Populations.

Notes on Figure 113.

The following samples were used as representative of thermogram shapes:

Rocks.

a. Sample no. 242. Normal coarse green silty tuff, Borr-owdale Volcanic Series. Minerals: chlorite, calcite, (illite); represents "average" Borrowdale Volcanic chloritic sedimentary rocks (these are variable, see above).

b. Sample no. 268. Light grey limestone of the Coniston Limestone series. Minerals: chlorite, calcite, (illite), (quartz); represents Palaeozoic post Borrowdale Volcanic chlor-itic sedimentary rocks (these are not so variable, see above).

Lake Sediments.

Soils and drift material give variable thermogram shapes and none of these is considered diagnostic at this stage.

c. Sample no. 167, clay fraction. Dark grey silt from the Late Glacial varved sequences. Minerals: K20 rich clay micas, chlorite, "300° endothermic", (quartz); represents the pink clay population of all Late Glacial lacustrine material, including pink clay bands in Post Glacial gyttja (see Chapter 21).

d. Sample no. 167, silt fraction. Minerals: chlorite, quartz, calcite, (illite); represents the dark grey silt popul-ation in silt and clay varves.

e. Sample no. 176, silt fraction. Pale grey sand from the Late Glacial varved sequences. Minerals: chlorite, quartz, calcite, (illite); this fraction represents, though they are not all identical, the pale grey population of the sandy lacustrine facies, including thin sandy layers in Post Glacial gyttja.

f. Sample no. 13, clay fraction. Surface ooze from Wind-

-ermere, April - May 1961. Minerals: K20 rich clay micas incl--uding illite, amorphous hydrated aluminosilicates, (chlorite), ("300 endothermic" in a few); represents the clay population of all Post Glacial lake deposits in Windermere (Chapter 22). This is the flocculating mineral population. The degree of hydration varies slightly in some "facies".

g. Sample no. 34, clay fraction. Surface ooze from Rydal Water, August 1962. Minerals: amorphous hydrated aluminosilic--ates, illite, (chlorite), ("300 endothermic" in a few); repres--ents the variations of the relative sizes of the major peaks.

h. Sample no. 13, silt fraction. Minerals: chlorite, illite, quartz, (amorphous hydrated aluminosilicates), ("300 endothermic" in a few); represents the silt populations of all Post Glacial organic lake deposits in the four lakes. There are slight variations equivalent to those of the clay fractions (see above, also see Chapter 30).

Chapter 29. Mineral Analyses of Heavy and Light Fractions of Fine Sand.

This work was not intensive; only a brief survey was made from 50 heavy mineral and 6 light mineral mounts (the samples are listed in table 35c). Material smaller than 0.422 mm (sieve mesh 36) was separated into fine sand, silt, and clay (fig. 81). The fine sand was further separated using pure bromo-form (S.G. 2.85 to 2.90) into the heavy and light fractions. These were split to obtain portions small enough to mount onto 3 x 1 inch fine graticule glass slides; unused sand was stored and labelled. 400 grains were counted on each slide guided by the graticule, using the Point Counter as for textural analyses (Chapter 16). The results are not included in this thesis bec-ause they were very inconclusive as far as this study went.

The predominant grains in both fractions were angular rock fragments. These were recognised by their greenish colour and their degree of opacity/translucence which both vary from grain to grain. These comprised an average of 85% of the total number counted in the heavy minerals and more than 90% in the light minerals. It is thought that the predominance, or lack, in each fragment, of one or more particularly heavy mineral(s) caused that fragment to sink or float in bromoform accordingly. This high proportion of the one category of grain would have made a selective analysis of each fraction useful, whereby the remain-ing 15% of the grains (10% in light fractions) would have been raised to the respective 100%'s. This was not done here. There was no evidence for trends from the pure mineral suites as exam-ined here but it is possible that sebction may have yielded more significant results. Also the silt fractions may have been of

interest in this respect.

Pure Heavy Minerals. (Milner, 1952, Chapter 9)

A few nearly euhedral colourless grains of zircon were recognised in all the heavy mounts by their high refractive ind--ex (R.I.) and prismatic habit. There were also a few angular grains of a dark brown garnet in some of the slides exhibiting isometric extinction. It is possible that there was confusion with rock fragments of certain other heavy mineral grains due to their apparently heterogeneous composition, to their comparatively weak translucence, and to their greenish colour. Epidote was thus present in some samples (it is occasionally found in the rocks, Chapter 30) as green angular grains without any habit but exhibiting small areas of apparently conchoidal fracture like "bottle glass". Angular yellow green grains of sphene were also seen though again they were only weakly translucent. Angular green - brown "patchy" barite grains (barytes) were also present. Biotite and all the mica or flaky minerals were conspicuously ab--sent from the heavy mineral slides.

Opaque Iron Oxides. These comprise the bulk of the pure mineral grains in all the heavy mounts and a selective an--alysis may have been more useful if these also had been elimin--ated. There are many sub-rounded haematite grains which were reddish brown in reflected light. Some apparently botryoidal limonite grains were yellow by reflected light. Some dull black authi--genetic pyrite grains were recognised. There were some perfec--tly spherical opaque grains in some of the slides which were very dark brown in reflected light; these may have been spherul--itic siderite. Patchy angular sphalerite (zinc blende) grains with a metallic lustre, brown in reflected light; and metallic

cleavage fragments of galena were recognised in a few. These metal ores, if present, were derived from the hydrothermal veins which have been used quite widely for mining purposes in the Lake District (Postlethwaite, 1913).

Pure Light Minerals. (Milner, 1952, Chapter 9)

A few angular white quartz grains were seen in most mounts. There was also a pale flaky mica, probably sericite, and some whitish altered grains, probably felspar. The flaky green rock fragments were assumed to be of predominantly chlor--itic rock; in no case was a single chlorite flake seen to form a sand grain.

Conclusions.

There are no conclusive data here but a selective anal--ysis may have provided some. The proportion of pure minerals is higher in the heavy fractions probably due to the concentrat--ions of opaque metal ores. The absence of mica or flaky min--erals in the heavy fractions suggests that biotite was in an al--tered state, possibly as chlorite in the rocks (Milner, loc. cit.). The absence of pure chlorite flakes from the light frac--tions suggests that this mineral is extremely fine grained throughout the basin.

Further investigations of these suites may have proved useful, particularly as Weaver (1963) postulates certain relat--ionships between the heavy minerals and the clay minerals of deposits containing both.

Chapter 30. Results of Qualitative Analyses.

Unlike the physical analyses, there is nothing to be gained here by expressing all the qualitative results indiv--idually; the samples, with locality nos. for reference to figure 19, which were analysed by one or more of the four methods are listed in table 35.

Comparison of D.T., X-ray, and Chemical Methods.

It has been emphasised that none of these three methods gives a complete mineral analysis. All quantitative methods are doubtful. Generally, however, the methods were used in conjunction to considerable advantage. X-ray analyses give a broad identification of the major constituents and approx--imate quantitative estimates are made by this method. In this respect, it would have been advantageous to have used a camera with a larger diameter. The inner lines of chlorite and illite are very important but neither their d-values nor their relat--ive intensities can be said to have been satisfactorily meas--ured on these films (fig. 111). D.T. analyses tend to show the variations of the major constituent to a greater extent. The particular advantage, at this stage, is the presence of the low temperature peak of dehydration (peak 1) on the thermograms. Also quartz and calcite are measured more accurately. Chemical analyses show the significance of some of the thermogram varia--tions and confirm some of these results; the former of these two will be of further importance when more data is available.

Mineralogy of Windermere Material.

Felspar, chlorite in the hydrated deposits, and illite in the non hydrated deposits were not detected with any

certainty on the thermograms but X-ray powder patterns confirm-ed their presence. Material which is both amorphous and therm-ally inert will have passed undetected altogether.

Lower Palaeozoic Rocks.

The Borrowdale Volcanic rocks consist largely of tuffs, which have undergone low grade metamorphism to a "green schist" facies. They exhibit varying textures, colours, and minor structures, and have been examined microscopically (Pink, pers-onal communication, 1963). Green chlorite comprises up to 15 or 20 percent of these rocks and is the most easily disting-uished mineral in the fine grained groundmass. This last also contains orthoclase, partly or wholly altered to sericite, cal-cite, opaque iron ores, rare quartz, and rarer epidote; plagio-clase phenocrysts are sometimes seen. As a result of the diff-erent analyses done in this work, the chlorite has been ident-ified as ripidolite and/or thuringite; calcite, quartz, and felspar were also identified. None of the true micas were found though they may be present. The lavas in this volcanic group, though they were not examined in detail, also appear to have been altered considerably because many of them contain apprec-iable quantities of chlorite and calcite. They are acid or in-termediate and may contain up to 10 or 15 percent of quartz, in contrast to the tuffs.

The post Borrowdale Volcanic rocks lie unconformably on this group (table 1) and consist largely of shales, greywack-es, grits, quartzites, and limestones some of which may be al-tered. Their mineralogy is more varied than that of the tuffs, though they again contain 15 to 20 percent chlorite with a more constant thermogram shape; 0 to 20 percent calcite, and sometimes

up to 25 percent quartz.

All the rocks may contain up to 20 percent illite (X-ray powder patterns).

Late Quaternary Unconsolidated Deposits.

These were always separated into silt and clay fract-ions before analysis though "full sediments" were sometimes anal-ysed also. Where altered (hydrated) material was present, the clay fractions showed a greater degree of hydration than the silt fractions, and contained a lower proportion of unaltered rock fragments, and a higher proportion of K_2O.

Boulder Clay. Mineralogy is varied and localised and no trends of any sort were detected. Chlorite is again the major identified constituent and the quartz content is often fairly high (> 30% in one case). The boulder clays are seldom more than slightly hydrated and illite is no more important than in the rocks. The "300 endothermic peak" is sometimes present though always small; calcite is absent. Most of the major peaks are medium sized to large though a feature of a few of the therm-ograms is that these are very small. It is uncertain whether this is due to the presence of a high proportion of thermally inert material or to the presence of chlorites and/or illites which are characterised by small peaks. Two boulder clay samples gave large dehydration effects in both fractions (see below); these are thought to be due to Post Glacial alteration of mater-ial which would not otherwise have given these large effects.

Soils. Mineralogy is also varied and localised. Chlor-ite (ripidolite, X-ray analyses) is the major identified const-ituent and the quartz content is often high. The "300 endother-

-mic" sometimes occurs fairly strongly on the clay fraction thermograms; calcite is absent. The clay fractions are generally fairly well hydrated; thus illite and amorphous aluminosilicates are probably important constituents of many soils though not all of them. Again two samples were strongly hydrated (see below).

Fluvioglacial and Deltaic Material. Mineralogy is not quite so varied and localised as boulder clays and soils. Ripid--olite (X-ray analyses) is the major identified constituent though partial hydration of much of the material suggests that illite and aluminosilicates may be fairly important. Quartz is present in the silt fractions in very variable proportions. The "300 endothermic" is not important and calcite is absent. The major peaks are generally medium sized to large. A feature of some of the clay fraction thermograms is an uneven base line; this has not been explained.

The two analysed rusty fluvioglacial clays gave large peaks 1 in both fractions. This is probably due to Post Glacial alteration of earlier material which was less hydrated. These rusty samples were always found on the lake floor in water shall--ow enough to allow wave action to affect the material. It is thought that this shallow "sub lacustrine" alteration caused the drift to be hydrated comparatively recently. Two each boulder clay and soil samples were also well hydrated (see above); these were probably altered likewise in the Post Glacial period but it is not known by what method.

Late Glacial Lacustrine Material. The most interesting mineralogical feature of these deposits is the fact that the clay fractions of the different facies (pink clay including clay bands in gyttja, dark grey silt, and pale grey "band" including thin

Post Glacial layers) and the equivalent silt fractions give diagnostic thermogram shapes for these respective particle popul--ations. The clay material is the same for all facies (fig. 113c), the silt material is the same for the predominant clay and silt facies (fig. 113d), and the "sand" material is similar for the pale grey facies (fig. 113e, this last did show variations in thermogram shape). Chlorite is the dominant mineral, the quartz and calcite (<8%) contents of the silt fractions are app--reciable (the latter in all but one sample, no. 32MP). They are both absent from the clay fractions. The "300 endothermic" is present in all the samples analysed though this may not be gener--al. There was no evidence for hydration but K20 rich micas are present, probably including some illite. The major constituent gives large peaks in all cases except the coarse pale grey "sand" where they are small.

Post Glacial Organic Lake Material. The mineralogy of reddish gyttja and surface ooze is similar though the observed variations may be significant. There is a high proportion of hydrated material, probably both illite and aluminosilicates. The clay fractions contain more hydrated material and K20 than the silt fractions (figs. 112g and 113 f and h). Quartz and unaltered chlorite are present, particularly in the silt fractions where quartz may be up to 5%. In some samples the "300 endotherm--ic" is relatively very strong and it is absent altogether in others. Calcite is generally absent. The clay bands and the sandy layers are of particular interest because they were non organic and similar to the Late Glacial facies. Thus they prov--ided the opportunity to assess the weathered state of the pure mineral matter entering the lake during the Post Glacial period.

In fact the clays are only slightly hydrated (fig. 113c) and the sands contain slightly less calcite, otherwise they are very similar in their thermogram shape to the normal Late Glacial facies. Thus it is inferred that the most important alteration to the minerals during the Post Glacial period was after the incorporation of organic matter by biological activity.

The major peaks are medium sized to large in normal Post Glacial material. Peak 2 temperature varies from 550° to 580°; when it is low peak 2 is lower than peak 1 and vice versa. Gyttja generally gives relatively small peaks 2 at about 550° in the clay fractions and 565° in the silt fractions; this is more stable throughout than the ooze. Ooze from Trips 1 and 5 also gives relatively small peaks 2 though the peak temperatures are often higher than the gyttja; Trip 2 coze gives relatively large peaks. The inference is that the ratio of illite to aluminosil-icates in these Post Glacial populations was variable and it was ~~high~~ low in gyttja and Trips 1 and 5 ooze.

Surface ooze from the three small lakes, collected bef-ore the floods in August 1962, gave very large peaks 1 and rel-atively small peaks 2 at between 540° and 550° (fig. 113g); the amorphous/illitic material ratio was higher here than in any Windermere material though these are taken as the same broad particle population.

Only one of the three near shore silts from Windermere gave sufficient clay fraction material to be analysed. Hydrated aluminosilicates are dominant probably with small amounts of illite, chlorite, and quartz. The silt fractions are only slight-ly hydrated, however, in which the major constituent is chlorite and there is up to 25% quartz; calcite is absent.

Chapter 31. Weathering Processes in the Windermere Basin.

This comprises a general summary of Late Quaternary weathering as deduced from the qualitative analyses in the prev--ious chapters. The conclusions are often used to obtain a more complete understanding of the physical processes of deposition and are thus often referred to in the previous Part III.

The parent rock material of most deposits in the basin probably occurred within the watersheds around the Windermere catchment area. The ice cap was largely local (Greswell, 1950) and natural processes are unlikely to have brought material in from outside since its recession. The first significant stage in Late Quaternary weathering of the rocks was the glacial mechan--ical breakdown and the subsequent deposition of the products as boulder clay. Apart from some soils and gravels on isolated patches of high ground which may have formed before the last glaciation, this boulder clay is the earliest existing post Lower Palaeozoic material in the basin (Pink, personal communic--ation, 1963). It was later subjected to Late Glacial mechanical and chemical weathering, resorting, and redistribution by melt-water in the valleys and, as typical varves, in the lake. These last suggest that there was then, as now, a large body of still or nearly still water filling the main valley of the North Basin, though there may also have been stagnant ice in parts the melting of which may have been a major cause of the slumping (Chapter 21). After the influence of the ice cap had disappeared, the boulder clay, the soils, and the other unconsolidated deposits (drift) in the valleys (also the exposed rocks to a small extent) were sub--ject to Post Glacial chemical and mechanical weathering and to stream erosion. They were deposited in the lake as organic rich

sediments, first reddish gyttja and, more recently, blackish surface ooze. Most of the soils in the basin may have started evolving at any time since the last glacial maximum. They comprise weathered rock and/or alteration products of earlier unconsolidated deposits such as boulder clay. They generally exhibit normal stratification in situ (Pink, personal communication, 1963; fig. 18). The simplified flow diagram for mineral matter in the basin is shown on figure 8.

Qualitative analyses of material representing these stages of the breakdown and decomposition of the parent rocks have been outlined in Chapter 30. The remainder of this chapter is devoted to discussing the mineralogy of these various stages, considering them particularly as responses to the environment of weathering and decomposition.

Hydration of the Major Constituent.

It has already been suggested that hydration may be related to interstitial water content (Chapters 21 and 22).

It will have become clear that peaks 2, 3, and 4 are common to almost all the major constituents in Windermere material, and that their shapes, sizes, and temperatures are dependant on factors as yet largely unknown. Peak 1, the low temperature peak of dehydration, however, is given only by certain unconsolidated deposits, more particularly their clay fractions, and not by the rocks to any significant extent. Size variations of this peak are taken as a direct measure of the degree of hydration. D.T. evidence alone, therefore, suggests that hydration of parent material is the most important single aspect of Late Quaternary chemical decomposition; also that the major constituent was effectively unchanged except that a proportion of

loosely sorbed molecular water was introduced between the molec--ular sheet layers. This is deduced entirely from thermogram "morphology". It is realised that a fundamental genetic study will certainly reveal a more complex situation. Weaver (1958) claims that cation adsorption is the most important parameter derived as a result of the weathering environment. This occurs as a result of unsatisfied charges in the lattice. The fact that K20 rich micas are concentrated in the clay fractions of all un--consolidated deposits (not only the hydrated Post Glacial illite), in contrast to the silt fractions and rocks, is an indication of this complex situation (fig. 112g). The hydrated material has been identified as amorphous aluminosilicate and/or illite. Illite is often termed "hydramica"; here its thermograms justi--fy the term "hydrachlorite".

The size of peak 1, therefore, is taken in this work as a measure of the degree of chemical decomposition of the par--ent material. These assumptions are in broad agreement with Weaver's conclusions (loc. cit.) which claim that the basic clay mineral lattice, inherited from the source material, is the prime factor in determining its final composition. The assimilated parameters are of secondary importance and reflect the environ--ment of deposition. Thus Weaver describes clays as predominant--ly detrital. Clay material requires long exposure to intense weathering and leaching agents and thus a slow burial before cat--ion adsorption becomes important.

A histogram diagram was drawn (fig. 114) for the height of peak 1 in the rocks, silt fractions, and the clay fractions, counting the total of each facies separately. A clear progress--ion of increasing peak height (1) can be outlined: rocks ⟶

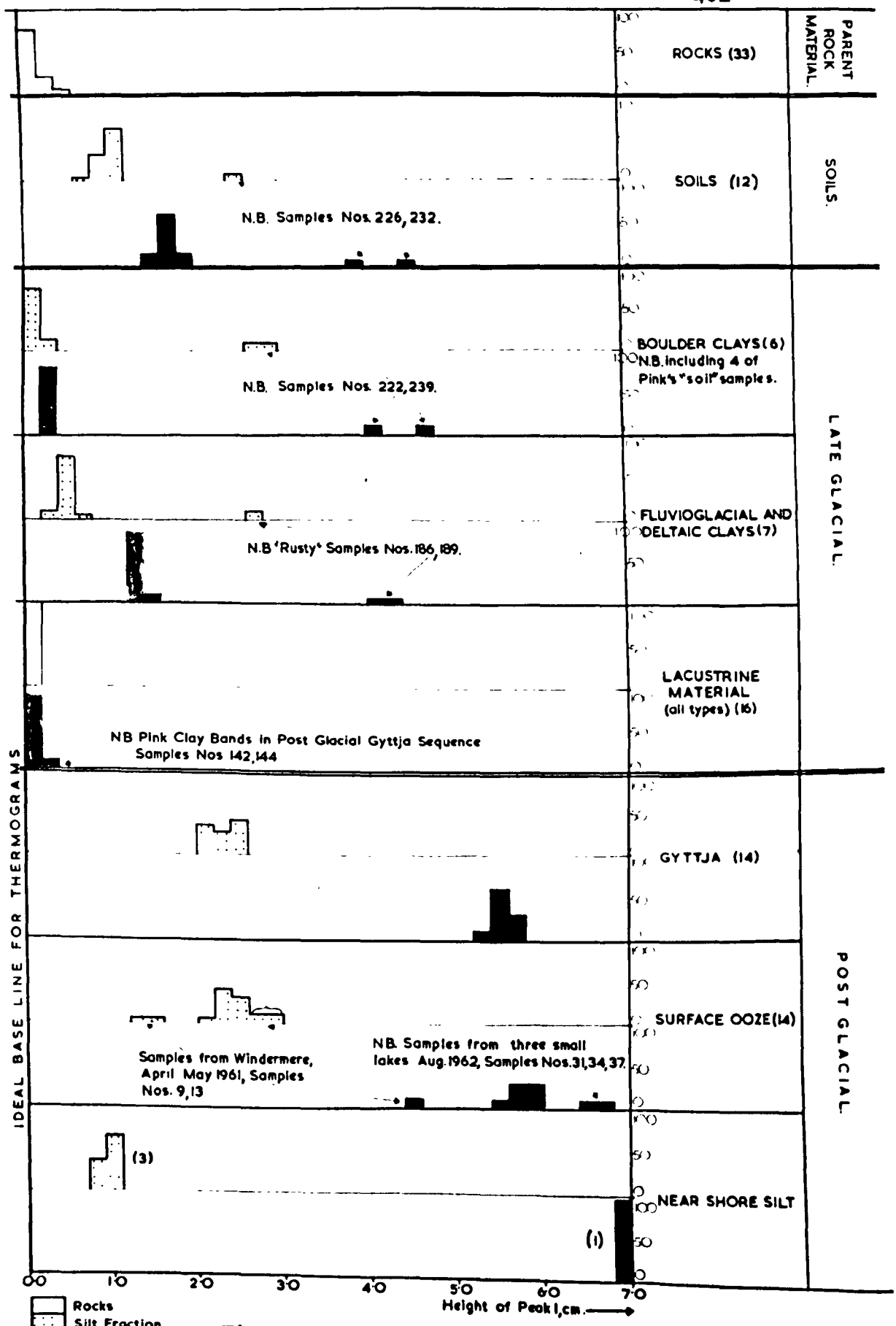


Figure 114. Histograms Showing Progressive Hydration.
(also see figure 113)

boulder clay → fluvioglacial clay → Post Glacial organic lake sediments. The silt fractions of the latter three facies giving a smaller peak than the clay fractions in each case. The exceptions, samples nos. 222, 239 (boulder clay); and 186, 189 (rusty fluvioglacial clay) were probably subject to abnormal Post Glacial decomposition (Chapter 30). This progression of increasing hydration is in agreement with the sequence of events since the last glacial maximum. The soils and Late Glacial lacustrine material, however, do not form obvious stages in the progression and are considered separately.

Soils. These are alteration products in situ, and for this reason, their state of decomposition is probably more varied than that of any other facies. It is significant that they are slightly more hydrated than the rocks, boulder clay, or fluvioglacial clay, the three facies of which they are most likely to be decomposition products. The soils have probably been undergoing gradual hydration throughout the Post Glacial period and are probably still doing so. Hydration of the two exceptional samples appears to have been very much more rapid for some reason.

It is unlikely that the Late Glacial lacustrine deposits were derived to any great extent from the hard rocks. Thus the early drift, when it was comparatively fresh, provided the sediment for redeposition as varved sequences in the lake. It is significant, therefore, that at present the drift material sampled and analysed here is more hydrated than the lacustrine material. Thus the drift has been subject to hydration and decomposition processes like the soils, especially the upper layers sampled here, since the derivation of the varves. These last

have been effectively protected from subsequent external alter-
-ation processes. The presence of calcite in lacustrine deposits supports this conclusion (see below).

Post Glacial Deposits. The hydration of Post Glacial material is significantly higher than that of most Late Glacial material; it is also significantly varied itself. The gyttja is fairly stable though ooze varies and these variations are import-
-ant in assessing the prevailing conditions (climatic and geograph-
-ical). This aspect has been considered in Part III, Chapter 23. It will be shown that near shore silts are mineralogically in the same category as other Post Glacial material and that the variat-
-ions seen on the histogram are due to its coarser particle size (see below).

The clay fractions of the pink clay bands of the trans-
-itional sequence, which are slightly hydrated, indicate that early Post Glacial hydration and weathering of the pure mineral matter was not effective until incorporation of the organic detri-
-tus as part of the deposit by biological activity. The same applies to the silt fractions of these clay bands and to those of the thin non organic pale grey sandy layers (which were similar to the lacustrine sand facies except that they contained less calcite). This signifies that Post Glacial hydration in the lake was controlled by the presence of organic matter.

Lake Environments as Indicated by Presence and Absence of Calcite.

Data about the presence or absence of calcite, as obtained by the qualitative analyses, are also important with respect to the aqueous environments in which Late Quaternary sediments were deposited and preserved. The following sections

concerning calcite analyses should be considered along with previous sections in Part III (Chapters 21 and 22) concerning pH and organic content; and also water content and flocculation (thus, indirectly, mechanical analyses).

Weakly Acidic Late Glacial Environments in the Main Lake.

It has been shown that there is an appreciable quantity of calcite in much of the parent material (rocks). Of the derived deposits, however, only the silt fractions of the Late Glacial lacustrine material contain it at present, and this in considerably reduced proportions. It is emphasised that carbonates are readily detected on the thermograms down to about 1.5% $CaCO_3$ (fig 112h). Calcite is attacked by an acidic aqueous environment as follows: $CaCO_3 + 2H^{+} \rightarrow Ca^{++} + H_2O + CO_2$. The inference is that calcite has been removed from the parent drift, or at any rate, from its upper sampled layers, by an acidic aqueous environment at some stage since the lacustrine deposits were derived from it. This is supported by the low median pH value of the drift (4.8; Chapter 21). The buried environment of the lacustrine deposits has protected the contained calcite from similar attack. Unfortunately the samples of lacustrine material were all too hard to test with the pH meter probe.

It is significant that calcite, while being found in the grey silt fractions, is not found in the pink clay fractions. There are two possible explanations for this:

a. That there is some chemically unaltered rock flour in the clay fraction but not in sufficient quantities to give a calcite peak on the thermograms. This is unlikely because the general thermogram shape suggests that there is a fair proportion of unaltered material in the clay grade.

b. That the silt sized grains were largely protected from corrosion by their size (surface area/volume ratio) while the smallest ones were not. This explanation is preferred because the silt grade calcite is reduced in proportion to the rocks (and is absent from one sample, no. 32MP). Thus a slightly acidic lake environment in Windermere is postulated during the deposit--ion of these lacustrine varves; though this may not have become effective until post depositional alteration had set in.

Strongly Acidic Post Glacial Lake Environments.

Calcite is conspicuously absent from the gyttja and the ooze. The boundary between calcite bearing varves and calcite free muds is sharp. It appears to coincide exactly with the sudden appearance of organic detritus in the sediments at the beg--inning of the Post Glacial period. The pH meter always gave the gyttja and ooze as acidic though with some variations in the intensity (gyttja median: 5.6; Windermere ooze: 5.9). This and the absence of calcite suggest that the weakly acidic environment in the lake became strongly acidic with the arrival of organic matter on the scene. Organic decomposition products, such as humic acid, promoted this sudden change; particularly in the bur--ied sediments subjected to strong decomposition. Thus any part--iculate calcite brought into the lake would have been removed during and/or after deposition. Mackereth (personal communicat--ion, 1963) also suggested that sulphuric acid is a decomposition product which lowers the pH due to oxidation of ferrous sulphide after sampling. The organic free calcite bearing non hydrated clay and sand layers indicate a very quick burial.

Acidic Environments Outside the Main Lake.

The lake environments were comparatively homogemeous in

contrast to those in shallow water and outside the lake, which may have showed considerable local variations. However, it has been shown that calcite was present in the early drift whereas the upper sampled layers are now calcite free and quite strongly acidic. This lowering of the pH is a general tendancy superimp--osed on the local variations as a result of soils occurring in situ on the drift, which were organic rich during the Post Glacial period. There was a general downwards percolation of their de--composition products.

In this respect there was probably a relationship bet--ween interstitial water content and weathering environment. The Late Glacial lake environment has been "compacted and protected" from external alteration; environments outside the lake, however, have been subjected to Post Glacial weathering and corrosion. It is significant that these last have had their interstitial water increased as well as their degree of hydration.

Coincidence of Hydration and Acidic Environments.

It is seen that in all the cases mentioned so far, the general rule using figure 114 appears to be that material formed in a strongly acidic environment is well hydrated, material formed in an environment which has altered is partially hydrated, and material formed in a weakly acidic environment is non hydrated. A relationship is thus postulated between the pH of the environ--ments of erosion, transport, deposition, and burial, and the deg--ree of hydration of the material formed in those environments. This relationship also appears to be dependant upon the control of hydration by the presence of organic matter (see above). It is, however, emphasised that these relationships are not fully understood and that they are certainly not simple whereby acidity

and organic matter cause the hydration of fine material.

There are several anomalous samples in this respect in which the material is well hydrated, in contrast to the facies norms: soil nos. 226, 232; boulder clay nos. 222, 239; fluvio--glacial clay nos. 186, 189. The last two samples are rusty clays taken in short cores from shallow water on the threshold region; they were probably exposed to wave action and well oxygenated water, if only spasmodically, and had grass roots in them as if they were soil. They passed downwards and outwards into fresh clay (fig. 63). The particular anomaly in these two cases is that their pH was significantly less strongly acidic than that of the only slightly hydrated fresh clays.

These six anomalies are an indication that the relation--ship between the degree of hydration and the pH and organic con--tent is not simple but that other environmental factors are also operative. For instance the redox potential (Eh) is vital to a more complete understanding of lake environments, of their acid--ity, and of their effects on these fine and therefore readily altered sediments. This is shown by Murray (1956; work on Lake Mendota outlined in Chapter 2) and Mackereth (personal communic--ation, 1963; work on general Windermere lake chemistry outlined in Chapter 20). The redox potential was not measured in this work.

Quartz Content of Windermere Material.

Thermograms do not exhibit the presence of quartz as readily as that of calcite. This is shown by many rocks whose powder patterns indicate quartz but whose thermograms do not. This is probably because the peak coincides with the steep under--side of peak 2 in these cases (fig. 109 a and c). Silt fractions

of unconsolidated material always contain a higher proportion of quartz than the corresponding clay fractions and often occurs in the former as sharp peaks 2 at about 580° (fig. 109 d, e, h). X-rays indicate that there is a trace of quartz in the clay fractions where none is observed on the thermograms. This suggests that rock flour does make up a significant proportion of most clay fractions. In general, the silt contains more quartz than the rocks so that mechanical breakdown products are concentrated in these coarser fractions. Certain boulder clay and soil samples contain exceptionally high concentrations of quartz in both fractions. This is due to local conditions and the composition of the parent rock.

Ratio of Decomposed Material/Unaltered Material.

There are two fundamental types of particle made available for transport and deposition as part of a sediment by weathering of parent material.

a. Chemical Decomposition Products. These are formed by hydration, cation exchange, leaching, and corrosion of parent material. They are flaky particles and are generally termed the "clay minerals" (Grim, 1953, p.1); they are said to be very small, seldom occurring larger than 0.002 mm. This is the reason for using this division between silt and clay fractions of Windermere material. Clay minerals are formed from material unstable in the chemical environments prevailing at any time between disintegration of parent material and the present. In this work hydration has been used as the criterion for the degree of decomposition of parent material, though the presence of other decomposition products containing concentrations of K_2O is realised.

b. Mechanical Disintegration Products. These are grains of pure minerals or rock fragments which are chemically stable in the prevailing conditions but have been subject to mechanical break--down from the parent material. Particles of any size may be found in this category, particularly in the boulder clay of a recently glaciated region such as Windermere. Those unaltered particles smaller than 0.002 mm are termed "rock flour".

The parent rocks in Windermere are generally fine grained, and rock fragments, as opposed to pure mineral grains, may be found in the finest grades of material in this category. Thus chloritic rock fragments are the most important disintegration products. Quartz is stable and its presence in a sample indicates a relatively high proportion of unaltered material. Calcite is un--stable and its significance has already been discussed; corros--ion of calcite is not considered as "decomposition" in this work for convenience. There may be some variations in the disint--egration products, stratigraphically with the morphological evol--ution of the basin, and contemporaneously in the different stream loads.

Thus ideal silt grade material would contain particles in the second category only while clay grade material would contain a mixture of particles in both categories, the proportion depend--ing on the degree of decomposition (hydration here) undergone prior to sampling. This ideal situation is shown in figure 1151. In practice, it is found that silt grade material is hydrated by an amount lower than, but approximately proportional to, that by which the clay fraction is hydrated. This decomposition of the silt fraction is considerably more than can be accounted for by the 13% of clay grade material found with the silt as a result of

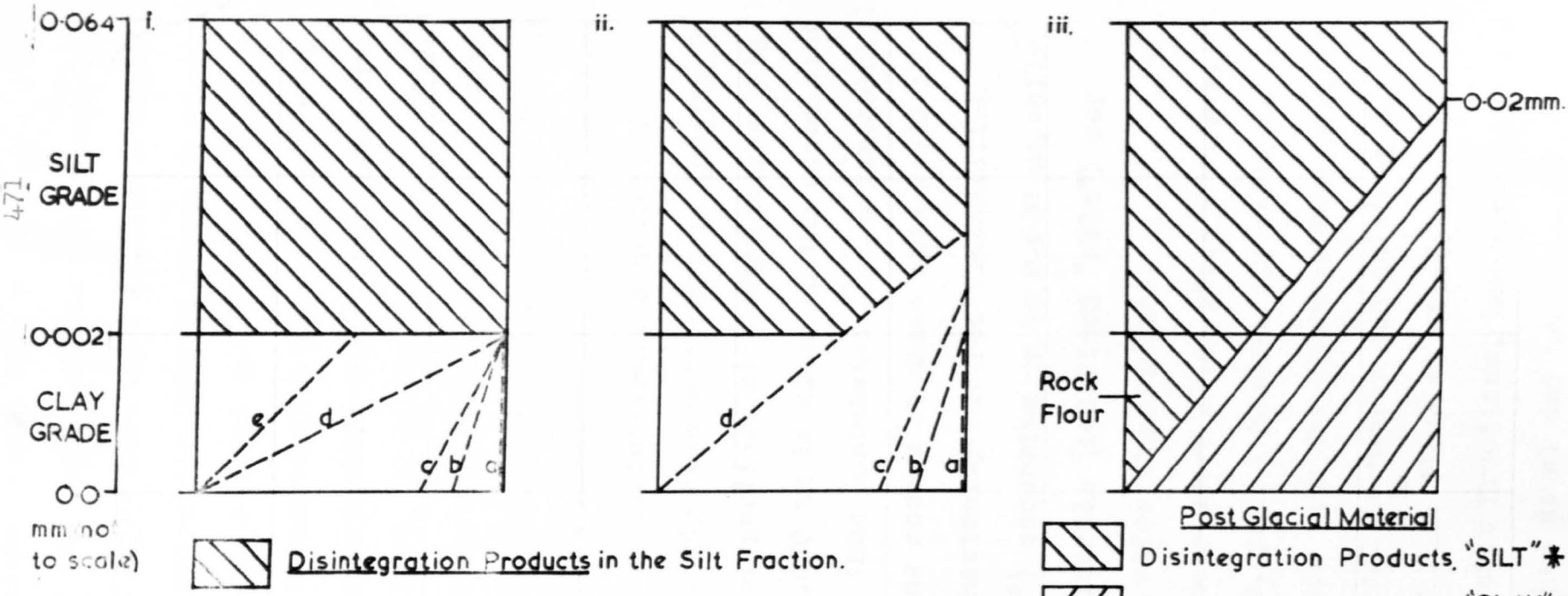


Figure 115. Distribution of Clay Minerals and Unaltered Rock Fragments in the two Fine Grades.

N.B. These diagrams should be read in conjunction with figure 68.

the imperfect separating technique (table 28); silt peak 1 sizes may be up to half the sizes of the corresponding clay peaks 1. The inference is that the silt grade here does contain a signif--icant proportion of hydrated material; this is shown in figure 115 ii and iii. Figure 115iii is devoted to Post Glacial mater--ial. The upper limit of the decomposition products is set at 0.020 mm because a number of experimental separations of Post Glacial material (sample nos. 4, 7, 8, 9, 13) produced fractions larger than 0.020 mm which gave no dehydration peak; that of the fraction smaller than 0.020 mm was slightly smaller than for the corresponding clay fractions as is expected due to further dilut--ion of decomposition products by disintegration products.

This discovery has already been mentioned in Chapter 20 as one basis for a discussion of particle size populations (fig. 68). It was also noted that 0.020 mm is close to the upper size limit of flocculation. It was thus postulated that a fundamental division of particle populations occurs at about this grade in Windermere. This concept of chemically altered flocculating clay minerals (redefined "clay") occurring up to 0.020 mm, while unaltered rock fragments and minerals (redefined "silt") may occur at any size, should have wider significance.

The clay fraction of near shore silts gives a larger, and the silt fraction a smaller, peak 1 because the particle size distribution is very much coarser than deeper water Post Glacial material. The clay grade material is nearly non existant and contains a negligible amount of rock flour to dilute peak 1. The disintegration products in the silt fractions, however, occur near--er the particle size maximum than usual and are correspondingly more important than the decomposition products. A mineralogical

comparison between deep water material and near shore silts on the basis of particle size is shown in figure 116 a and b.

Most of the Post Glacial and Late Glacial deposits ex-amined here have particle size distributions similar to that in figure 116b. It is valid, therefore, to consider together the two figures 115 i, ii, and iii and figure 116b to gain a true under-standing of the distribution of the two populations in the two fractions of the different facies. The result of this, when figure 115iii is superimposed on figure 116b, is shown in figure 116c; this represents Post Glacial lake sediments. The sand grade and, in-deed, the pebbles, come into the "silt" category. In this respect, fine sand analyses of lake sediments showed a preponderance of rock fragments with rare pure mineral grains (Chapter 29). Individual flakes even of chlorite were not confirmed.

Summary of Products and Processes of Weathering.

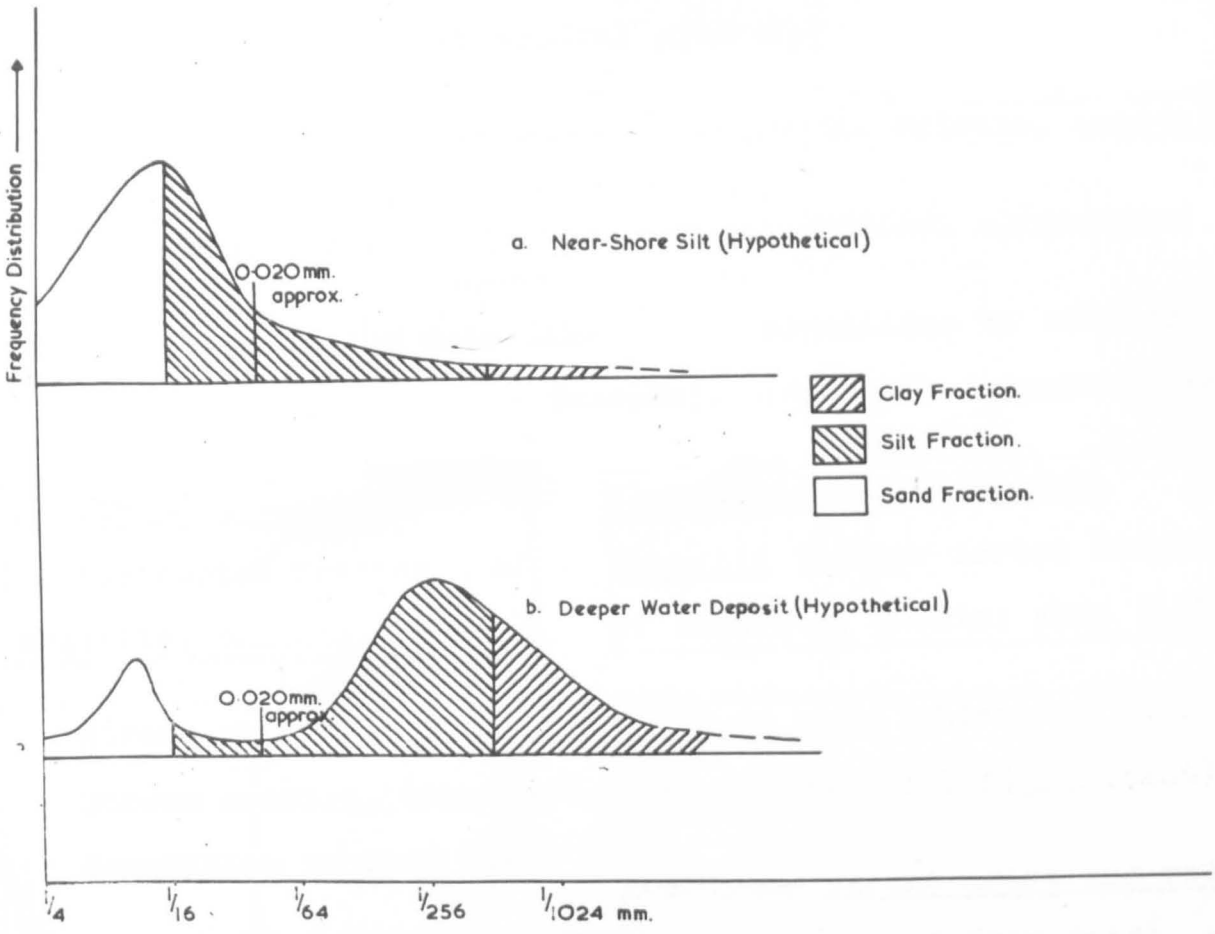
Products. Complete distribution of particles in Winder-mere sediments: Pebbles and coarse sand. Rock fragments and occasional vein quartz fragments.

Fine sand. Rock fragments; also quartz and occasional pure mineral grains.

Silt. Disintegration products, largely pure minerals are normal in this grade. Here the disintegration prod-ucts are largely rock fragments. Smaller than 0.020 mm there is a high proportion of decomposition products (Post Glacial only).

Clay. Decomposition products and rock flour.

Processes. A chart summarising Late Quaternary weather-ing processes in Windermere is shown in figure 117. This is based on the simple mechanical chart in figure 8.



c. Deeper Water Deposit showing distribution of disintegration and decomposition products in the size grades and fractions. (N.B. Scale doubled).

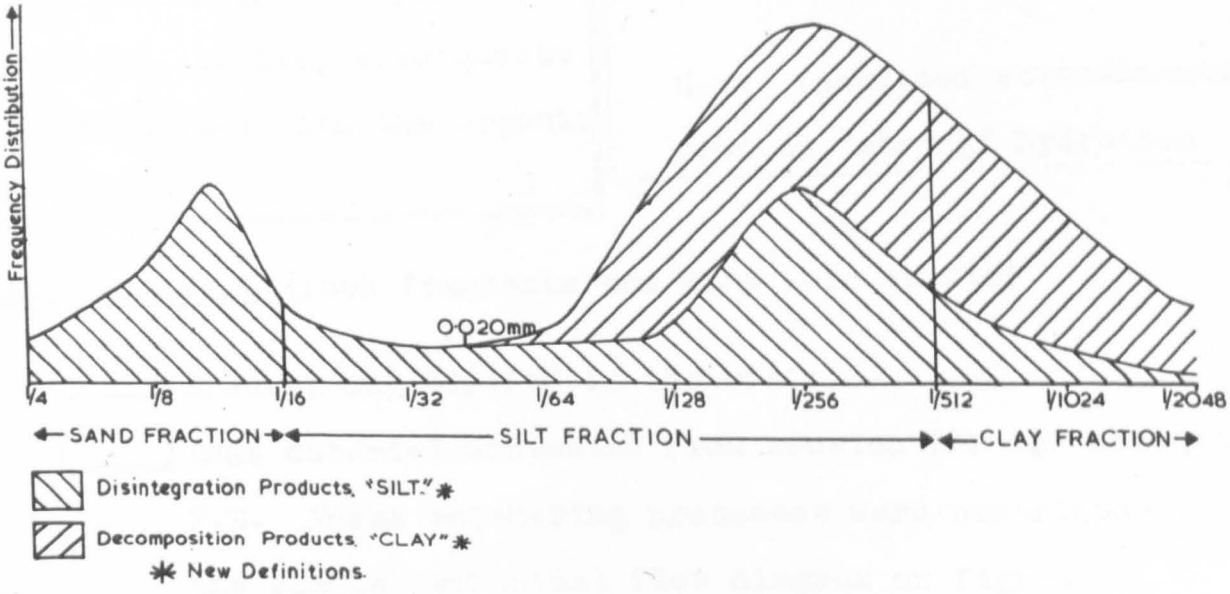
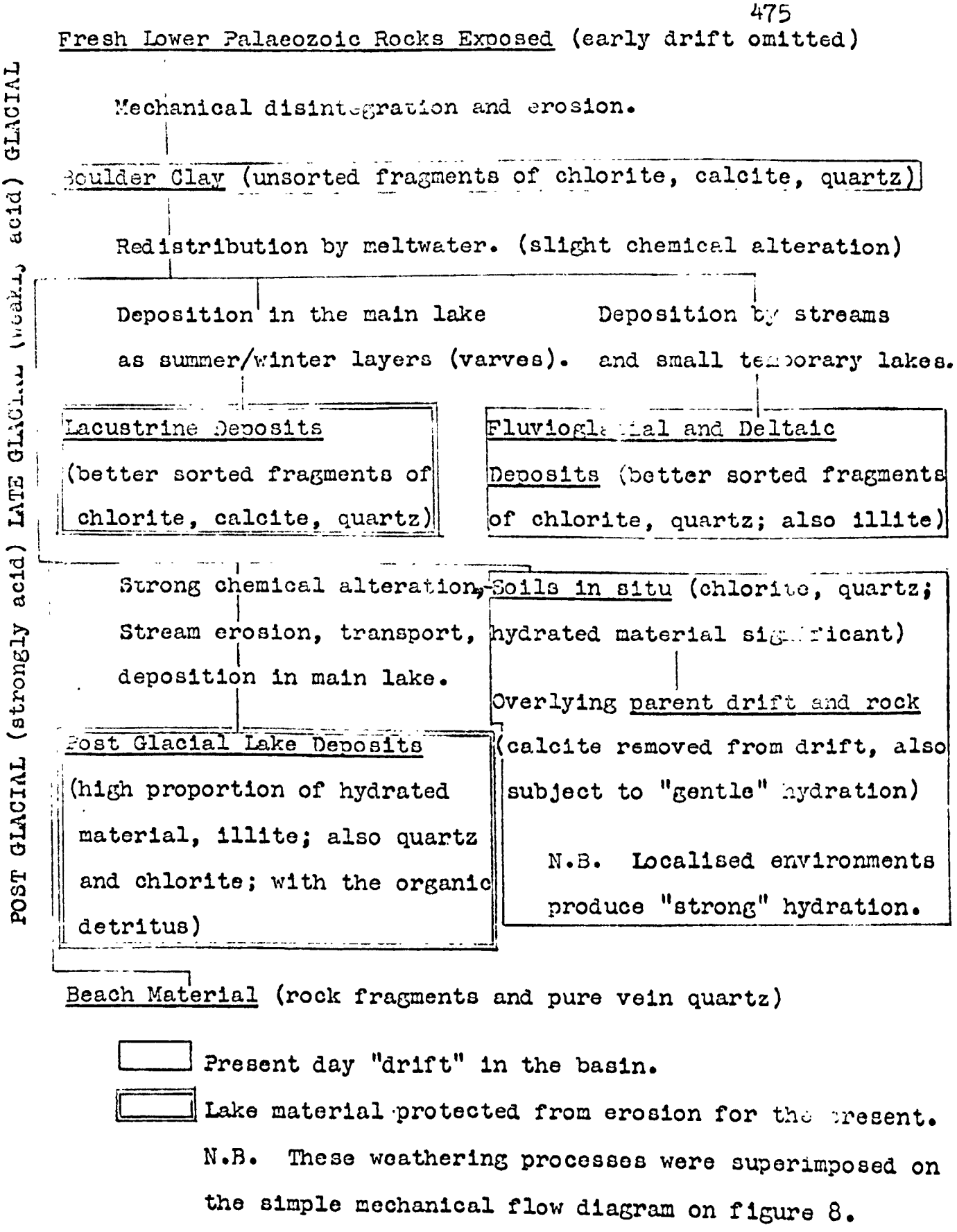


Figure 116. Frequency Diagrams Showing Silt and Clay Fractions of Post Glacial Material. (see also fig. 68)



N.B. These weathering processes were superimposed on the simple mechanical flow diagram on figure 8.

Figure 117. Summary of Weathering in the Late Quaternary.

PART V. SUMMARY OF CONCLUSIONS.

(The main sedimentological conclusions have been outlined at the ends of Part III, miscellaneous and physical results in Chapter 23, and of Part IV, qualitative results in Chapter 31. Previous to these, the conclusions from examinations of the various analysing techniques are discussed in Chapter 15. All the samples were classified with respect to their environ--ments of deposition as the first stage in reducing the multi--farious data to a manageable state, particularly through the triangular diagram, in Chapter 17.)

There remain two fundamental considerations which are thought to be of wider significance.

The Importance of Organic Matter in Sedimentation.

It has been shown that the influx of vegetable det--ritus which marked the beginning of the Post Glacial period, and the resulting acid decomposition products, caused fundament--al changes in lake sedimentation. The graded discrete Late Glacial settling of clay, silt, and sand fractions changed to homogeneous flocculated settling in the Post Glacial. In more recent times a proportion of this vegetable detritus has been replaced by an influx of sewage. Sedimentation remained fundam--entally similar but the strength of flocculation and the degree of hydration of the clay minerals both increased sharply. This indicates that not only does the physical presence of org--anic matter control sedimentation, but that so does the form it takes; and also that sewage pollution is an even more effective controlling factor than the decomposition products of vegetable detritus.

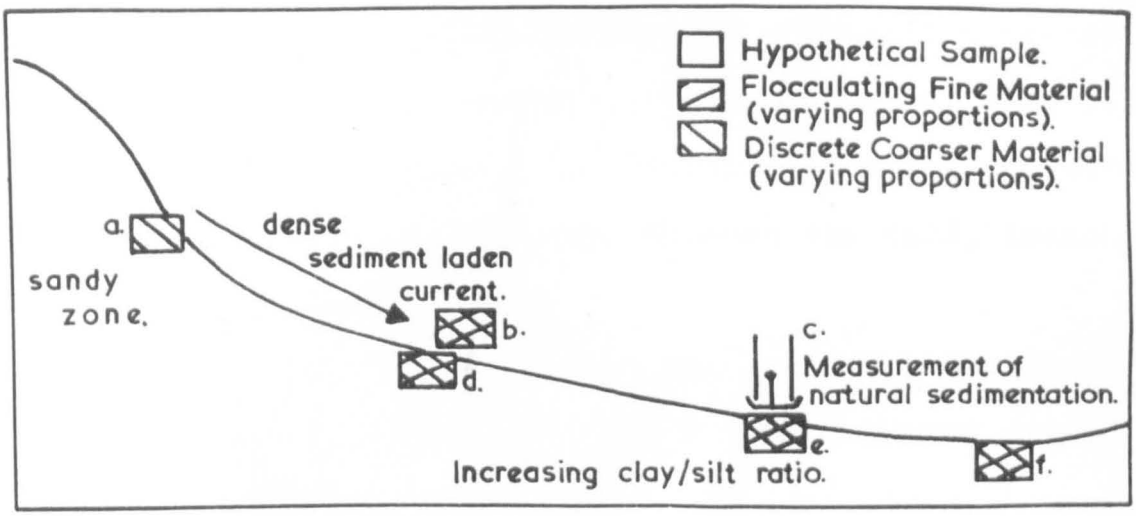
The process whereby biological activity incorporates organic matter to become an integral part of the lake sediments

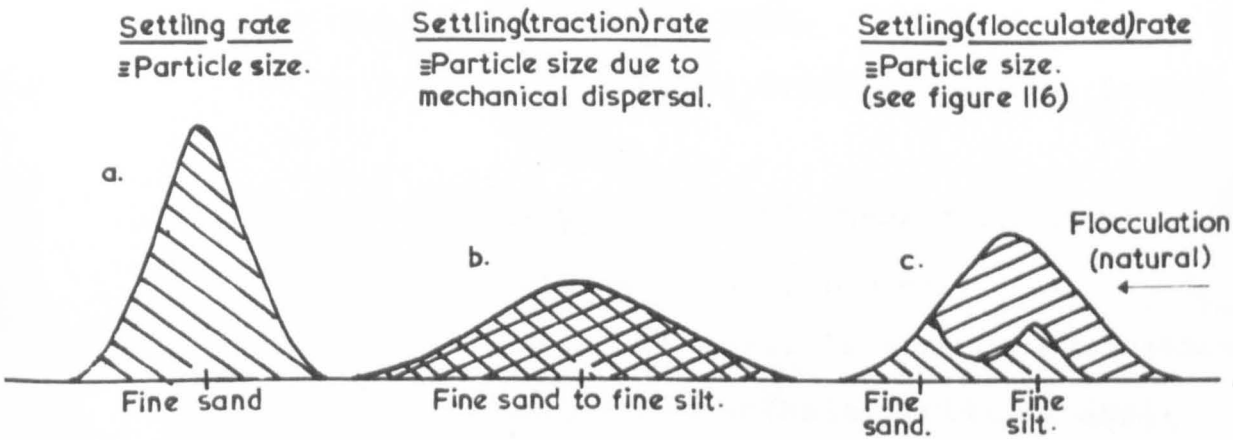
is also a fundamental sedimentological control. This is seen in the greater degree of clay mineral alteration by hydration, and also of flocculation, in lake sediments than in organic bearing drift material; also by the fact that these two groups give similarly trending, but mutually displaced, groupings on scatter diagrams concerned with organic content.

Hydration of clay minerals is controlled by the presence and type of organic matter, and also by the degree of acidity in the environment from weathering to deposition and burial. Thus, though the relationship must remain obscure, organic matter controls acidity.

Mechanical Distributions, Mineral Populations and Lake Sedimentation.

Four mineralogical types of sedimentary material have been distinguished in Windermere: two clay populations and two silt populations, Late Glacial and Post Glacial respectively. Graded discrete settling of pink non hydrated clay, dark and light grey calcite bearing silt, and "sand" was a comparatively simple "approximately log normal" mechanical process. Assymmetry, and occasionally bimodality, was introduced to the size distributions by finer pink clay particles settling "below their level" and being incorporated as admixtures in the grey silt material. Flocculated Post Glacial settling, however, is a complex process involving the reorganisation of size grades and of the particle populations. This is illustrated in figure 118.





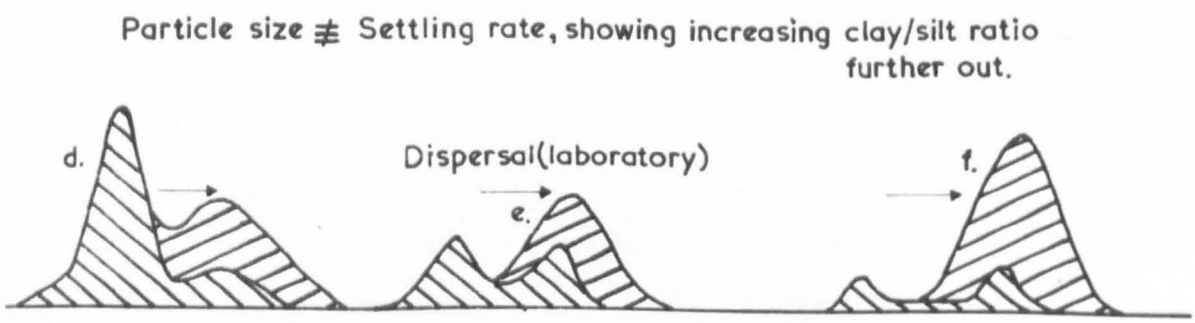


Figure 118. Mechanical Distributions to Illustrate the Reorganisation of Particle Populations during Sedimentation.

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APPENDIX.

Appendix No. 1. An Alphabetical List of Important Abbreviations.

C Test Constant for the Sedimentation Balance.

c A rapid method for calculating c.

d Settling solid particle diameter.

F.B.A. Freshwater Biological Association.

g Acceleration due to gravity.

h Distance a solid particle settles in a liquid (cms).

k, K Kurtosis of fine and coarse distributions respectively.

Md, MD Median diameter of fine and coarse distributions.

p Weight settled from suspension (gms).

P (mechanical calculations) Total weight in suspension.

P (statistical applications) Probability.

P90, P10 Ten and ninety percentiles (cumulative curves).

Q3, Q1 First and third quartiles (cumulative curves).

r radius of a solid particle (specifically in cms).

Sk, SK Skewness of fine and coarse distributions.

So, SO Sorting of fine and coarse distributions.

S.G. Specific gravity - general term.

t Time taken for particle to settle through h cms.

$T_o + T_r$ Time between on and off for centrifuge manipulation.

U.C.L. University College London.

v Settling velocity (specifically in cms/sec).

σ Solid specific gravity (mechanical calculations).

η Liquid viscosity (poise units).

ρ Liquid specific gravity (mechanical calculations).

χ^2 Chi squared (X^2 is used in the script for convenience).

There are many other abbreviations but these are the only ones that appear in this thesis in sections other than those with their own specific symbol keys.

Figures i (cores) and ii (trip maps), both accompanying Appendix No. 2, are to be found folded in at the back of this volume.

Appendix No. 2. A Journal of Visits to Windermere, Field Notes, and Descriptions of Samples and Localities.

Trip No. 1. 1st - 8th January 1961.

Purpose of Visit: To test the two siltmeters (Acknowl--edgements) and to collect a preliminary batch of sediment samples. Surface ooze and clays from the shallow "threshold" were taken with the F.B.A. Surface Sampler. Localities and samples are tabulated in table 1, plotted onto Trip Map No. 1 (fig. 1a), and described: (N.B. Table 1 is found at the end of this Appendix)

(N.B. "Normal Ooze" is defined as the dark brown semi liquid material near the sediment surface on the lake floor and includes the dark grey semi plastic material which grades up into it(see above).

There is generally a sharp boundary underneath this ooze but occasionally it is seen rather to grade into the reddish gyttja beneath.

The figures in brackets after the descriptions of localities refer to the weights in pounds dropped with the sampler for optimum penetration.

S1. 3 cms semi liquid brown ooze with fresh grass stalks overlying hard white rusty clay (25).

S2. 2.5 cms semi liquid brown ooze with fresh grass(10).

S3. 3 cms semi liquid brown ooze with fresh grass stalks overlying hard white clay; hard white nodules in the ooze near the junction with the clay (20).

S4. 5 cms normal ooze overlying reddish gyttja (10).

S5. 8 cms normal ooze overlying reddish gyttja (10).

S6. 8 cms normal ooze overlying reddish gyttja (10).

S7. 9 cms normal ooze overlying reddish gyttja (10).

S8. 22 cms normal ooze overlying reddish gyttja; gradual boundary between ooze and gyttja (15).

S9. 3 cms semi liquid brown ooze with fresh grass stalks overlying hard pale brown clay; hard nodules in the ooze near the junction with the clay (20).

S10. 5 cms normal ooze overlying hard smooth green clay (20).

S11. 16 cms normal ooze overlying a hard rusty khaki clay; gradual junction with smooth clay underneath (25).

S12. 8 cms normal ooze overlying reddish gyttja; there was a rounded pebble in the ooze with the fresh grass stalks (10).

S13. 1 cm semi liquid brown ooze "drifting" on top of a light brown rusty clay (20).

S14. 15 cms normal ooze overlying a small patch of hard white clay; a second sampling operation at the same locality shows the ooze overlying reddish gyttja (20).

S15. 14 cms normal ooze overlying reddish gyttja (10).

S16. 14 cms normal ooze overlying pale grey hard and smooth sandy clay (25).

S17. 3 cms normal ooze overlying pale hard smooth green clay (25).

S18. 6 cms normal ooze overlying reddish gyttja (10).

S19. 7.5 cms normal ooze overlying reddish gyttja (10).

S20. 1.5 cms semi liquid brown ooze overlying hard pale rusty clay (20).

S21. No material brought up over this area suggesting that

the lake floor was semi liquid, sandy, or stony at this point (20, 25, 30).

S22. 14 cms normal ooze overlying reddish gyttja (10).

S23 16 cms normal ooze overlying reddish gyttja with leaf beds; both deposits contain a proportion of white gritty material (15).

S24. 16 cms normal ooze overlying reddish gyttja; leaves are concentrated at a horizon about 10 cms below the top, these were collected as part of the ooze sample (15).

Trip No. 2. 28th April - 5th May 1961.

Purpose of Visit: To collect further samples of surface ooze using the "spot sampling" technique for the first time; also to collect gyttja from the surface samples and the first batch of core samples. Localities and samples are tabulated in table 1; plotted onto Trip Map No. 2 (fig. 1b), and described:

S1. 10 cms normal ooze overlying reddish gyttja (10).

S2. 3.0 - 6.5 cms normal ooze overlying reddish gyttja (10).

S3. No material brought up over this area suggesting that the lake floor was semi liquid, stony, or sandy at this point (20, 25, 30).

S4. 21 - 24 cms normal ooze with leaves concentrated at a horizon about 10 cms below the top. Gyttja was not penetrated (30).

S5. 24 cms normal ooze, gyttja not penetrated (30).

S6. 8 cms normal ooze overlying reddish gyttja (10).

S7. 18 cms normal ooze with leaves concentrated at a horizon about 10 cms below the top overlying reddish gyttja (20).

S8. 6.5 cms normal ooze overlying reddish gyttja (10).

C1. There was a comparatively gradual boundary near the top, at approximately 65 cms depth, from gyttja to black material; this boundary coincided with a textural change to almost semi-liquid material. The material above was sampled as ooze and that immediately below as gyttja.

See figure ii, Core No. 1.

C2. Same boundary as at C1, at a depth of 22 cms. The bottom cradle (No. 4) was misplaced in transit and the top-most clay band was neither observed nor measured in the field; the position of the B - level gyttja was estimated as shown in figure ii, Core No. 2.

C3. See figure ii, Core No. 3.

C4. See figure ii, Core No. 4.

C5. See figuer ii, Core No. 5.

Trip No. 3. 7th - 13th October 1961.

Purpose of Visit: To collect further samples of pale clay in the F.B.A. Surface Sampler from the shallow "threshold" region, using the "spot sampling" technique. Also to collect a further batch of cores; the core sampler developed an air leak and only two cores were taken. Localities

and samples are tabulated in table 1; plotted onto Trip Map No. 3 (fig. 10); and described:

S1. A veneer of liquid "ooze" drifting on the surface of hard smooth pale clay (25).

S2. A veneer of liquid "ooze" drifting on the surface of pale clay; this was varied in texture throughout and is described as "rusty" (15).

S3. 1.5 cms liquid "ooze" drifting on the top of a reddish, spongy textured, "rusty" clay. This graded sharply down into smooth pale brown clay at a depth of 10 cms (25).

S4. No ooze at this locality; grass growing on the surface of a "rusty", gritty clay (25).

S5. 2.5 cms semi liquid ooze, with grass growing in it, overlying a very hard smooth pale yellow clay; it was only possible to extract one sample here because of the hardness of the clay (30).

S6. A veneer of liquid "ooze", with grass growing in it, overlying a pale green "rusty" clay; there was a gradual transition to smooth yellow clay at about 12.5 cms depth (20).

S7. No material was brought up over this area, probably due to the extremely hard packed surface of the clay at this point (30).

S8. No ooze at this locality; a hard gritty clay, "rusty" in patches, was sampled (25).

C1. See figure ii. Core No. 6.

C2. See figure ii, Core No. 7.

(N.B. After these two cores had been taken the corer developed an air leak which made the last phase of the operation difficult: that of extracting the drum and coring tube from the soft sediment on the lake floor. Several attempts were made to haul the apparatus up with a block and tackle before a diver was sent down to release the pressure inside the drum.)

Trip No. 4. 24th - 30th June 1962.

Purpose of Visit: To collect shoreline and island samples; beach material, near shore silts, and Late Glacial material either underlying beach material or exposed at the back of beach cuttings. The entire lake shore and the islands were surveyed; exposures, recent sediments and features of topographical interest were noted. The appear-ance of two old beach platform levels at several places near the lake shore is particularly important in this respect. These observations are summarised in Trip Map No. 4 (fig. id); the localities and samples are tabulated in table i, plotted onto the Trip Map, and described:

N.B. When a sample is described using particle size (such as "well sorted") or roundness (such as "well rounded") terms, the description is as assessed in the field.

B1. Medium sized sub rounded pebbles are found on the beaches at Coatlap Point; the northern, central, and southern beaches were sampled. Present day beach material appears to be derived, in part anyway, from earlier beach platform material. There is one level about 5 feet above the lake and a second about 25 feet above it; these are assumed to be ancient beach platforms and are termed the "five foot" and "25 foot" platforms respectively. the beach basement was not seen.

B2. Basement of gritty clay bound together by grass roots; this material was also exposed in the eroded cutting behind the beach. Present day beach material was pebbly.

B3. Soft loose silty deposit in about one meter depth of water (termed "near shore silt"); this merged with pebbly beach material in shallower water and on the beach itself. The basement was not seen.

B4. This locality was a small bay under cover of trees and sheltered from the south by a solid rock promontary (roches moutonées); the basement was not seen. The beach material was very distinctly separated into three "shoestrings" of coarse sub rounded pebbles near the water's edge, coarse sand about three feet further back, and behind this was a nearly pure organic detritus deposit.

B5. Near shore silt in about one meter depth was sheltered by a fallen tree and contained a high proportion of large organic detritus; the beach material was distinctly sep--arated as at B4.

B6. Near shore silt in about one meter of water.

B7. Basement of hard packed clay varying in colour. The beach material was sub rounded and pebbly.

B8. Same as B7.

B9. Same as B7; clayey basement predominantly yellow.

B10. Same as B9; beach material separated into three "shoestrings".

B11. Sandy soil bound together by grass roots, lying in hollows in the solid rock about two feet above the lake.

B12. Same as B10; clayey basement grey and yellow.

B13. This locality was a small bay cut by wave erosion into gritty clay; it was sampled about three feet above lake level. There was clear evidence for a five foot platform at this point, while the 25 foot platform was only seen in a few places.

B14. Small beach cut by wave erosion into pebbly alluvium; two "shoestring" deposits were seen on the beach, sand at the water's edge was sampled.

B15. Same as B14.

B16. Very small bay cut by wave erosion into clay bound together by grass roots; the surface of this is seen to dip under the the pebbly sub-rounded beach material towards the lake, forming a basement.

B17. Same as B16.

B18. Same as B16.

B19. Part of a long beach with deep sand for most of its length; it is backed at this point by a narrow rocky ridge

running inland; this is a roches moutonées and on the beach itself there is a striated pavement showing north - south striations. The rest of the beach is backed by Late Glacial material consisting of pebbly clay or cross bedded sands and silts overlain by alluvial material. At this locality the pavement dips towards the lake under a pale hard packed clay which is overlain by a semi cemented rusty coloured coarse sandstone. Present day beach material oversteps these three parts of the basement. All the junctions are sharp (fig. id, Inset No. 1).

B20. Further along the same beach as B19 the coarse beach sand at the water's edge was sampled.

B21. The same beach "hooks" to the north around Cockshott Point to form a sandy spit enclosing marshy ground. Fine sand was sampled at the water's edge.

B22. A pebbly beach; sand at the water's edge was sampled; no basement seen.

B23. Same as B22; a gritty clay basement was sampled.

B24. Same as B22; basement not seen.

B25. The River Troutbeck has cut down through the extensive area of flat land approximately equivalent to the five foot platform; on the north bank about 50 yards from where the river enters the lake, a section across the strata was seen. About two feet below river level, a hard white clayey material was seen underlying a layer of hard grey silt three or four feet thick. The area is covered by a veneer of alluvial material (soil with pebbles and some boulders). In places

the silt has collapsed due to undercutting by the river. The sequence is shown in figure id, Inset No. 2.

B26. A small beach cut into earlier material though the latter was not exposed at this point; sand at the water's edge was sampled.

B27. An extensive beach cut into the hard grey silt.

B28. Same beach as at B27; the pale clay was exposed below the silt. Sand was sampled at the water's edge.

B29. A beach cut into earlier material containing thick deposits of fine sand, this was sampled at the water's edge.

B30. Beach material was mainly pebbles and angular boulders based on the solid Coniston Limestone outcropping at Holme Crag; coarse sand at the water's edge was sampled.

B31. Same as B30.

B32. Same as B30.

B33. A beach section across the strata forming the extensive flat lying area near the delta of the River Brathay; the section is similar to that at Troutbeck and it shown in fig. id, Inset No. 3. The pebbly alluvium is absent at this point and the swampy vegetation was based on the hard grey silt. This silt contained a higher proportion of sandy layers than at Troutbeck. The silt was sampled.

B34. The same strata were cut at this point by the River Brathay; there was no alluvial material overlying the silt.

B35. The clay/silt boundary was seen to be gradual compared to Troutbeck. In this beach section sand was sampled at the water's edge.

B36. Sandy beach material was distinctly separated into three

"shoestrings"; fine sand at the water's edge was sampled.

B37. Thompson's Holme; pebbly clay in a beach section sheltered under tree roots.

B38. Same as B37.

B39. Pale smooth clay lying directly on the rock outcrop which forms the "crag and tail" shoulder of the western Lily of the Valley island; the clay is exposed in a narrow beach inlet south of the outcrop.

B40. Pebbly and clayey soil protected by tree roots in a beach section at the southern end (tail) of the same island.

B41. Pebbly clay lying directly on the central "crag and tail" of Belle Isle.

B42. Sandy clay exposed in a small bay on the eastern side of Belle Isle.

Trip No. 5. 19th - 26th August 1962.

Purpose of Visit: To collect further samples of surface ooze from Windermere, of particular interest after the recent storms during the earlier part of August. Also to collect surface ooze samples, three each, from Grasmere, Rydal Water, and Elter Water; these samples had been collected, before the storm by members of the F.B.A., and stored in the Jenkin Surface Sampler tubes. Localities and samples are tabulated in table 1, plotted onto Trip Map No. 5 (fig. 1e), and described;

S1. 12.5 cms normal ooze overlying reddish gyttja with a gradual transition (10). N.B. Estimated near to S7, Trip 1.

S2. 30 cms normal ooze with leaves at a horizon about 18 cms below the surface; gyttja not penetrated (15).

N.B. Estimated near to S8, Trip 1.

S3. 10 cms normal ooze overlying reddish gyttja with a gradual transition (10).

S4. 10 cms normal ooze overlying reddish gyttja with a gradual transition (10).

S5. 8.5 cms normal ooze overlying reddish gyttja (10).

S6. 10 cms normal ooze overlying reddish gyttja (10).

S7. 10 cms normal ooze overlying reddish gyttja with a gradual transition (10).

S8. No material was brought up at this point (cp. S4, Trip 2). The swollen river was probably scouring the lake floor after the recent storms.

S9. 20.5 cms normal ooze with green vegetable fragments (moss and twigs) overlying reddish gyttja with a gradual transition. The gyttja was semi plastic as usual but here it contained fragments of fresh green moss as well as a proportion of white gritty material (20).

S10. 3.5 cms semi liquid ooze overlying reddish gyttja (10).

S11. 5 cms normal ooze overlying reddish gyttja (10).

N.B. Estimated near to S7, Trip 2.

S12. 9 cms normal ooze overlying reddish gyttja (10).

N.B. Estimated near to S8, Trip 2.

S13. 2.5 cms semi liquid ooze overlying reddish gyttja (10).

N.B. Estimated near to S1, Trip 2.

Localities S14 - S22 were in the three small lakes. The short cores that were preserved in the tubes were varied in length but they were all normal ooze and none of the tubes had penetrated any gyttja that there may be in these lakes.

Trip No. 6. 9th - 10th November 1962.

Purpose of Visit: To collect two samples of gyttja in a surface sampler from the shallow "threshold"; these were taken with the Jenkin Sampler. Also to collect core samples which had been taken by members of the F.B.A. during October. Localities and samples are tabulated in table i, plotted onto Trip Map No. 6 (fig. if), and described:

S1. 4.5 cms normal ooze overlying reddish gyttja (10).

S2. 3.5 cms normal ooze overlying reddish gyttja (10).

C1. See figure ii, Core No. 8.

C2. See figure ii, Core No. 9.

C3. See figure ii, Core No. 10.

C4. See figure ii, Core No. 11.

C5. See figure ii, Core No. 12.

C6. See figure ii, Core No. 13.

C7. The two cores were not examined.

C8. See figure ii, Core No. 15.

C9. Core not examined.

C10. See figure ii, Core No. 17.

C11. The two cores were not examined.

Notes on table 1:

*: Sample numbers of preliminary samples taken during Trip 1 and given a full examination later.

*1: No samples taken probably because the lake floor was composed of loose silt or sand.

*2: No samples taken because the lake floor was very hard clay; 30 lbs were used but were found to be insufficient for penetration.

*3: Cores not examined in detail because they are to be used at a later stage for a series of soil mechanics experiments to determine the nature of the slumping in the Late Glacial material.

L.G. Late Glacial material.

P.G. Post Glacial material.

Where a sample is one of a facies (clay for example) from a varved sequence, it is denoted by: L.G. Clay layer; where the varves are not discernible, it is denoted by L.G. Clay.

SE etc. Estimated compass bearings.

1,2,3 etc. in the third column refer to the points of reference in table 3.

Table 1. Field Notes Catalogued.

Trip No. 1 (Localities on figure 1a)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
S1	-	25 yds S. of 22	3.0	Ooze	1	-	P1	PWH
S2	-	0 yds S. of 22	6.0	Ooze	2	-	P2	PWH
S3	-	20 yds S. of 21	2.5	Ooze	3	-	P3	PWH
S4	-	100 yds S. of 21	17.0	Ooze	4	-	P4	PWH MCK
S5	S2	3-4: 16° 13'; 4-5: 70° 15'.	11.5	Ooze	5	61	P5 *2	PWH MCK
S6	-	3-4: 20° 15'; 4-5: 78° 15'.	23.5	Ooze	6	-	P6	PWH MCK
S7	S3	3-4: 0° 0'; 4-5: 40° 0'.	-	Ooze	7	60	P7 *3	PWH MCK
S8	S1	100yds S. of 2	11.0	Ooze	8	62	P8 *1	PWH MCK
S9	S32	50 yds S. of 17	3.5	Ooze	9	-	P9	
				Ooze	10	65	P10 *5	PWH
S10	-	50 yds SE. of 17	4.0	Ooze	13	-	P13	
				Ooze	15	-	P15	PWH
S11	S39	40 yds S. of 22	4.5	Ooze	21	-	P21	
				Ooze	23	-	P23	
				Clay	16	-	P16	PWH
				Clay	19	68	P19 *90	
S12	-	25 yds W. of Thompson's Holme	4.5	Ooze	17	-	P17	
				Ooze	18	-	P18	PWH

Table 1. Field Notes Catalogued.

Trip No. 1 (Localities on figure 1a)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Date Sheet No.	Sample No.	Collectors
S13	S30	50 yds W. of Thompson's Holme	4.5	Ooze	24	-	P24	PWH
				Ooze	50	66	P50 *4	
				Clay	29	-	P29	
				Clay	25	67	P25 *204	
				Clay	26	-	P26	
S14	-	W. of Thompson's Holme; 25 yds off shoreline	5.0	Ooze	43	-	P43	PWH
				Ooze	20	-	P20	
				Clay	37	-	P37	
				Clay	45	-	P45	
S15	S40	14-16: 12° 19'; 16-15: 9° 0'.	9.0	Ooze	22	59	P22 *8	PWH
				Ooze	30	-	P30	
S16	S37	16-17: 41° 43'; 50 yds S. of 15.	4.5	Ooze	44	63	P44 *6	PWH
				Ooze	36	-	P36	
				Clay	49	-	P49	
				Clay	34	70	P34 *208	
S17	S36	16-17: 51° 18'; 25 yds S. of 17.	4.5	Ooze	42	-	P42	PWH
				Clay	35	69	P35 *207	
S18	-	16-17: 0° 0'; 50 yds N. of 18.	7.0	Ooze	53	-	P53	PWH
				Ooze	41	-	P41	
S19	-	16-17: 8° 55'; 100 yds NE. of 17.	17.0	Ooze	27	-	P27	PWH
				Ooze	48	-	P48	

Table 1. Field Notes Catalogued.

Trip No.1 (Localities on figure 1a)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
S20	S38	25 yds E. of Fir Holme	-	Ooze	40		P40	PWH
				Ooze	40A	4	P40A *7	
S21	-	100 yds N. of 11	1.5-5.0	No samples taken at this locality *1				
S22	-	100 yds N. of 11	17.0	Ooze	46	-	P46	PWH
				Ooze	47		P47	
S23	-	100 yds N. of 11	21.0	Ooze	38	-	P38	PWH
				Ooze	51	-	P51	
S24		100 yds N. of 11	37.5	Ooze	32	-	P32	PWH
				Ooze	33	-	P33	

Table 1. Field Notes Catalogued.

Trip No. 2 (Localities on figure 1b)

Field Locality No.	Cat. Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
S1	S25	17-19: 41° 20'; 19-18: 37° 30'.	13.0	Ooze	61	12	17	PWH
				A - Gyttja	56	10	86	
S2	S22	17-19: 25° 30'; 19-18: 11° 35'.	13.0	Ooze	71767981.	1	16	PWH
				A - Gyttja	60	11	84	
S3	S12	Area off Troutbeck	20 - 40	No samples taken at this locality *1				
S4	S14	11-12: 34° 10'; 12-14: 80° 15'.	36.0	Ooze	55	9	12	PWH
S5	S15	11-12: 39° 40'; 12-14: 57° 40'.	39.0	Ooze	72,80,78.	5	13	PWH
S6	S11	11-12: 30° 30'; 12-14: 9° 5'.	30.0	Ooze	73,75.	8	11	PWH
				A - Gyttja	69,70.	7	81	
S7	S18	15-16: 80° 10'; 16-17: 4° 10'.	44.0	Ooze	63,68.	4	14	PWH
				A - Gyttja	74,77.	6	89	
S8	S21	15-16: 40° 10'; 16-17: 11° 20'.	37.0	Ooze	64,67.	3	15	PWH
				A - Gyttja	65,66.	2	83	
C1	C1	1- 3: 103° 0'; 1- 2: 61° 0'.	19.0	Ooze	Core No. 1	13	9	FP
				A - Gyttja	Core No. 1	23	66	BW
				B - Gyttja	Core No. 1	24	88	PWH
				C - Gyttja	Core No. 1	25	102	

Table 1. Field Notes Catalogued.

Trip No. 2 (Localities on figure 1b)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
C2	C2	1- 2: 29° 0′; 2- 4: 49° 18′.	46.0	Ooze	Core No. 2	55	10	FP
				A - Gyttja	Core No. 2	26	67	BW
				B - Gyttja	Core No. 2	27	89	PWH
C3	C10	7-13: 64° 40′; 7- 8: 21° 50′.	39.0	A - Gyttja	Core No. 3	30	75	ER
				B - Gyttja	Core No. 3	29	97	JP
				C - Gyttja	Core No. 3	39	111	PWH
C4	C11	7-13: 55° 50′; 7- 8: 19° 40′.	39.0	A - Gyttja	Core No. 4	57	76	
				B - Gyttja	Core No. 4	31	98	ER
				C - Gyttja	Core No. 4	32	112	JP
				D - Gyttja	Core No. 4	33	123	PWH
				L.G.Sand layer	Core No. 4	56	175	
				L.G.Sand layer	Core No. 4	44	176	
C5	C12	7- 13: 47° 40′; 7 - 8: 19° 10′.	39.0	A - Gyttja	Core No. 5	33	77	
				B - Gyttja	Core No. 5	34	99	
				C - Gyttja	Core No. 5	35	113	
				D - Gyttja	Core No. 5	36	124	
				L.G.Sand layer	Core No. 5	45	177	ER
				L.G.Clay layer	Core No. 5	46	157	JP
				L.G.Silt layer	Core No. 5	47	167	PWH
				L.G.Clay layer	Core No. 5	48	158	
				L.G.Silt layer	Core No. 5	49	168	
				L.G.Clay layer	Core No. 5	50	159	

Table 1. Field Notes Catalogued.

Trip No. 3 (Localities on figure 1c)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
S1	S28	23-16: 104° 57'; 16-14: 22° 15'.	4.5	Smooth Clay	103,105.	14	203	PWH
S2	S29	23-16: 112° 0'; 16-24: 19° 15'.	4.0	Rusty Clay	107,108.	15	187	PWH
S3	S27	25-16: 102° 30'; 16-14: 21° 30'.	4.0	Rusty Clay	104,106.	16	186	PWH
				Smooth Clay	102	17	202	
S4	S26	25-16: 98° 14'; 16-14: 21° 13'.	2.5	Rusty Clay	92	18	185	PWH
S5	S31	23-24: 2° 52'; 16-14: 15° 42'.	3.0	Smooth Clay	93	19	205	PWH
S6	S33	9-14: 36° 45'; 14-16: 16° 4'.	3.5	Rusty Clay	97	20	188	PWH
				Smooth Clay	96	21	206	
S7 a,b	S34	West of 18	3.5	No samples taken at this locality *2				PWH
S8	S35	Between 15 and 16	3.0	Rusty Clay	94	22	189	PWH

Trip No. 3 (Localities on figure 1c)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
C1	C3	3- 5: 12° 38'; 5- 7: 60° 27'.	39.0	A - Gyttja	Core No. 6	37	68	
				B - Gyttja	Core No. 6	38	92	
				C - Gyttja	Core No. 6	39	104	
				D - Gyttja	Core No. 6	40	117	ER
				L.G.Pebble layer	Core No. 6	51	145 179	BW
				L.G.Pebble layer	Core No. 6	52	146 180	PWH
				L.G.Clay layer	Core No. 6	53	147	
				L.G.Pebble layer	Core No. 6	54	148 181	
C2	C4	3- 5: 18° 56'; 5- 7: 74° 33'.	53.0	A - Gyttja	Core No. 7	41	69	ER
				B - Gyttja	Core No. 7	42	91	BW
				C - Gyttja	Core No. 7	43	105	PWH

Table 1. Field Notes Catalogued.

Trip No. 4 (Localities on figure id)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
B1	B34	(see map)	-	Beach Sand	111	71a	56	PWH
				Beach Sand	114	71b	57	
				Beach Sand	115	71c	58	
B2	B33	"	-	L.G. Clay	112	117	223	PWH
B3	B32	"	-	Near-Shore-Silt	123	72	41	PWH
B4	B31	"	-	Beach Pebbles	113	73	54	PWH
				Beach Sand	113a	74	55	
B5	B26	"	-	Near-Shore-Silt	119	75	40	PWH
B6	B25	"	-	Near-Shore-Silt	117	76	39	PWH
B7	B24	"	-	L.G. Clay	130	118	222	PWH
B8	B23	"	-	L.G. Clay	122	119	221	PWH
B9	B20	"	-	L.G. Clay	124	120	220	PWH
B10	B16	"	-	Beach Sand	120	77	51	PWH
				L.G. Clay	116	121	192	
B11	B10	"	-	L.G. Sand	128	122	209	PWH
B12	B9	"	-	Beach Sand	121	78	47	PWH
				L.G. Clay	127	123	218	
B13	B8	"	-	L.G. Clay	126	124	191	PWH
B14	B42	"	-	Beach Sand	146	79	65	PWH
B15	B41	"	-	Beach Sand	153	80	66	PWH
B16	B40	"	-	L.G. Clay	109	125	201	PWH

Table i. Field Notes Catalogued.

Trip No. 4 (Localities on figure id)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
B17	B39	(see map)	-	Beach Sand	155	81	63	PWH
				L.G. Clay	140	126	200	
B18	B38	"	-	Beach Sand	145	82	62	PWH
B19	B37	"	-	Beach Sand	147	83	61	PWH
				L.G. Clay	91	127	199	
				L.G. Sand	164	128	210	
B20	B36	"	-	Beach Sand	131	84	60	PWH
B21	B35	"	-	Beach Sand	110	85	59	PWH
B22	B17	"	-	Beach Sand	161	86	52	PWH
B23	B18	"	-	L.G. Clay	141	129	219	PWH
B24	B19	"	-	Beach Sand	150	87	53	PWH
B25	B15	"	-	L.G. Silt	98	-	-	PWH
B26	B14	"	-	Beach Sand	137	88	50	PWH
B27	B13	"	-	L.G. Silt	139	130	217	PWH
B28	B12	"	-	Beach Sand	134	89	49	PWH
				L.G. Clay	136	131	212	
				L.G. Silt	99	132	216	
B29	B11	"	-	Beach Sand	135	90	48	PWH
B30	B5	"	-	Beach Sand	148	91	44	PWH
B31	B6	"	-	Beach Sand	163	92	45	PWH
B32	B7	"	-	Beach Sand	162	93	46	PWH
B33	B3	"	-	L.G. Silt	125	133	214	PWH

Table 1. Field Notes Catalogued.

Trip No. 4 (Localities on figure id)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
B34	B2	(see map)	-	L.G. Silt	100	134	21	PWH
B35	B4	"	-	Beach Sand	133	94	43	PWH
				Organic Detritus	118	-	-	
				L.G. Clay	132	135	211	
				L.G. Silt	130	136	215	
B36	B1	"	-	Beach Sand	129	93	42	PWH
B37	B21	"	-	L.G. Clay	186	137	194	PWH
B38	B22	"	-	L.G. Clay	187	138	195	PWH
B39	B27	"	-	L.G. Clay	183	139	196	PWH
B40	B28	"	-	L.G. Clay	197	140	197	PWH
B41	B29	"	-	L.G. Clay	193	141	198	PWH
B42	B30	"	-	L.G. Clay	101	142	193	PWH

Table 1. Field Notes Catalogued.

Trip No. 5 (Localities on figure 1e)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
S1	S4	7-13: 16° 40'; 7- 8: 31° 30'.	40.0	Ooze	182-4spots	105	18	PWH
S2	S5	7-13: 21° 30'; 7- 8: 32° 10'.	15.0	Ooze	190-4spots	106	19	PWH
S3	S6	1- 6: 4° 30'; 1- 5: 51° 0'.	47.5	Ooze	185-4spots	107	20	PWH
S4	S7	1- 6: 15° 15'; 6- 7: 77° 25'.	59.0	Ooze	199-4spots	108	21	PWH
S5	S8	7- 6: 31° 30'; 6- 8: 91° 50'.	21.5	Ooze	188-4spots	109	22	PWH
S6	S9	7- 1: 43° 0'; 1- 6: 11° 50'.	21.5	Ooze	184-4spots	110	23	PWH
S7	S10	14-13: 33° 30'; 13- 7: 103° 30'.	16.0	Ooze	192-4spots	111	24	PWH
S8	S13	Area off Troutbeck	36.0	No samples taken at this locality *1		-	-	PWH
S9	S16	13- 7: 71° 55'; 7- 8: 28° 10'	45.0	Ooze	180-4spots	112	25	PWH
S10	S17	(see map)	16.5	Ooze	198-4spots	11	26	PWH

Trip No. 5 (Localities on figure 1e)

Field Locality No. / Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
S11 S19	7- 8: 17° 50′; 14-15: 4° 20′.	30.0	Ooze	181-4spots	114	27	PWH
S12 S20	17-19: 41° 20′; 19-18: 37° 30′.	40.5	Ooze	194-4spots	115	28	PWH
S13 S23	14-15: 43° 20′; 14- 8: 5° 10′.	17.0	Ooze	189-4spots	113	29	PWH
	N.B. Members of the Freshwater Biological Association collected the following nine samples from the three small lakes in the Jenkin Surface Sampler and stored them in the tubes; the accurate locality and depth of water were not recorded and only one spot sample was taken in each case.						
S14	S42	Grasmere - inlet	-	Ooze	165	96	30 -
S15	S43	Grasmere - deepest	-	Ooze	166	97	31 -
S16	S44	Grasmere - outlet	-	Ooze	167	98	32 -
S17	S45	Rydal Water-inlet	-	Ooze	168	99	33 -
S18	S46	Rydal Water-deepest	-	Ooze	169	100	34 -
S19	S47	Rydal Water-outlet	-	Ooze	170	101	35 -
S20	S48	Elter Water-inlet	-	Ooze	171	102	36 -
S21	S49	Elter Water-deepest	-	Ooze	172	103	37 -
S22	S50	Elter Water-outlet	-	Ooze	173	104	38 -

Table 1. Field Notes Catalogued.

Trip No. 5 (Localities on figure 1e)

Field Locality No. / Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
S11 S19	7- 8: 17° 50'; 14-15: 4° 20'.	30.0	Ooze	181-4spots	114	27	PWH
S12 S20	17-19: 41° 20'; 19-18: 37° 30'.	40.5	Ooze	194-4spots	115	28	PWH
S13 S23	14-15: 43° 20'; 14- 8: 5° 10'.	17.0	Ooze	189-4spots	116	29	PWH

N.B. Members of the Freshwater Biological Association collected the following nine samples from the three small lakes in the Jenkin Surface Sampler and stored them in the tubes; the accurate locality and depth of water were not recorded and only one spot sample was taken in each case.

S14	S42	Grasmere - inlet	-	Ooze	165	96	30	-
S15	S43	Grasmere - deepest	-	Ooze	166	97	31	-
S16	S44	Grasmere - outlet	-	Ooze	167	98	32	-
S17	S45	Rydal Water-inlet	-	Ooze	168	99	33	-
S18	S46	Rydal Water-deepest	-	Ooze	169	100	34	-
S19	S47	Rydal Water-outlet	-	Ooze	170	101	35	-
S20	S48	Elter Water-inlet	-	Ooze	171	102	36	-
S21	S49	Elter Water-deepest	-	Ooze	172	103	37	-
S22	S50	Elter Water-outlet	-	Ooze	173	104	38	-

Table i. Field Notes Catalogued.

Trip No. 6 (Localities on figure if)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
S1	S2	(see map)	10.0	A - Gyttja	179	143	85	PWH
S2	S4	(see map)	10.5	A - Gyttja	178	144	87	PWH
		N.B. Members of the Freshwater Biological Association collected the following thirteen cores. The depth of water at each locality was taken accurately and the position determined with a sextant.						
C1	C5	(see map)	37.0	A - Gyttja	Core No. 8[illegible]		70	
				B - Gyttja	Core No. 8[illegible]		92	
				C - Gyttja	Core No. 8196		106	-
				D - Gyttja	Core No. 8197		118	
				L.G. Clay	Core No. 8[illegible]		149	
C2	C6	(see map)	62.0	A - Gyttja	Core No. 9[illegible]		71	
				B - Gyttja	Core No. 9[illegible]		92	
				C - Gyttja	Core No. 9[illegible]		107	
				D - Gyttja	Core No. 9201		[illegible]	-
				Top Clay Band	Core No. 9[illegible]		1[illegible]	
				Sand layer in Gyttja	Core No. 9[illegible]		1[illegible]	
				L.G. Clay	Core No. 9[illegible]		[illegible]	

Table i. Field Notes Catalogued.

Trip No. 6 (Localities on figure if)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
C3	C7	(see map)	25.0	A - Gyttja	Core No.10	203	72	
				e - Gyttja	Core No.10	225	127	
				f - Gyttja	Core No.10	226	129	
				B - Gyttja	Core No.10	202	94	
				G - Gyttja	Core No.10	227	131	
				h - Gyttja	Core No.10	228	133	—
				C - Gyttja	Core No.10	204	108	
				i - Gyttja	Core No.10	[illegible]	135	
				D - Gyttja	Core No.10	[illegible]	120	
				L.G. Clay	Core No.10	[illegible]	151	
				L.G. Clay	Core No.10	262	152	
				L.G. Sand layer	Core No.10	264	174	
C4	C8	(see map)	25.0	A - Gyttja	Core No.11	206	73	
				e - Gyttja	Core No.11	230	128	
				f - Gyttja	Core No.11	231	130	
				B - Gyttja	Core No.11	207	95	
				G - Gyttja	Core No.11	232	132	—
				h - Gyttja	Core No.11	[illegible]	[illegible]	
				C - Gyttja	Core No.11	[illegible]	[illegible]	
				i - Gyttja	Core No.11	234	136	
				D - Gyttja	Core No.11	209	121	

(continued on next sheet, xv)

Table 1. Field Notes Catalogued.

Trip No. 6 (Localities on figure if)

Field Locality No. / Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Data Sheet No.	Sample No.	Collectors
C4 C8	(see map)	25.0	Clay layer in Gyttja	Core No.11	256	143	-
N.B.	Continued from last sheet, xiv.		L.G. Clay	Core No.11	257	153	
			L.G. Pebble layer	Core No.11	258	154 182	
C5 C9	(see map)	57.0	A - Gyttja	Core No.12	210	74	
			B - Gyttja	Core No.12	211	90	
			C - Gyttja	Core No.12	212	110	
			Top Clay Band	Core No.12		144	-
			D - Gyttja	Core No.12	213	122	
			L.G. Clay	Core No.12	241	155	
			L.G. Clay-Vivianite	Core No.12	242	156	
			L.G. Silt layer	Core No.12	243	166	
C6 C13	(see map)	44.0	A - Gyttja	Core No.13	214	79	
			Coze layer -("coke")	Core No.13	215	140	
			B - Gyttja	Core No.13	215	100	-
			C - Gyttja	Core No.13	216	114	
			Sand layer in Gyttja	Core No.13	236	135	
			Sand layer in Gyttja	Core No.13	237	139	
C7 C14	(see map)	40.0	Neither core was ex-amined in detail	Core No.14 #3	-	-	-
				Core No.19	-	-	-

Table 1. Field Notes Catalogued.

Trip No. (Localities on figure if)

Field Locality No.	Catalogue Locality No.	Position	Depth (metres)	Facies	Spot or Core Nos.	Drill Sheet No.	Sample No.	Collectors
				A - Gyttja	Core No.15	[illegible]	79	
				Ooze layer-("coke")	Core No.15	[illegible]	141	
				B - Gyttja	Core No.15	218	101	
				C - Gyttja	Core No.15	219	115	
				D - Gyttja	Core No.15	[illegible]	125	
				L.G. Clay layer	Core No.15	[illegible]	160	
C8	C15	(see map)	35.0	L.G. Silt layer	Core No.15	245	169	-
				L.G. Pebble layer	Core No.15	246	163 161	
				L.G. Clay layer	Core No.15	247	162	
				L.G. Silt layer	Core No.15	248	170	
				L.G. Clay layer	Core No.15	249	163	
				L.G. Sand layer	Core No.15	250	178	
				L.G. Silt layer	Core No.15	251	171	
				L.G. Clay layer	Core No.15	252	164	
C9	C16	(see map)	24.0	Not examined in detail	Core No.16	-	-	-
				A - Gyttja	Core No.17	[illegible]	80	
				B - Gyttja	Core No.17	[illegible]	102	
				C - Gyttja	Core No.17	223	116	
C10	C17	(see map)	22.0	D - Gyttja	Core No.17	224	129	-
				L.G. Pebble layer	Core No.17	253	[illegible]	
				L.G. Silt layer	Core No.17	[illegible]	173	
				L.G. Clay layer	Core No.17	255	165	

Appendix No. 3. Preliminary Samples - Treatment and Results.

Thirty seven samples of surface ooze from all over the lake, and ten samples of clay from the shallow "threshold" region between the North and South Basins of the lake, were analysed in the early stages of this work (Chapter 8). the locality nos. are found on trip map No. 1 (fig. ia), sample nos. and results are found in table ii. The methods used for obtaining the preliminary data was simple and it is outlined in the flow sheet on figure iii.

The conclusions based on this work are considered in Chapter 8.

N.B. Notes on table ii:

(*): catalogue sample nos of preliminary samples which were given a full analysis at a later stage.

** : Data affected by gritty material in the surface ooze. Roundness numbers were determined in the preliminary tests for roundness, Chapter 16.

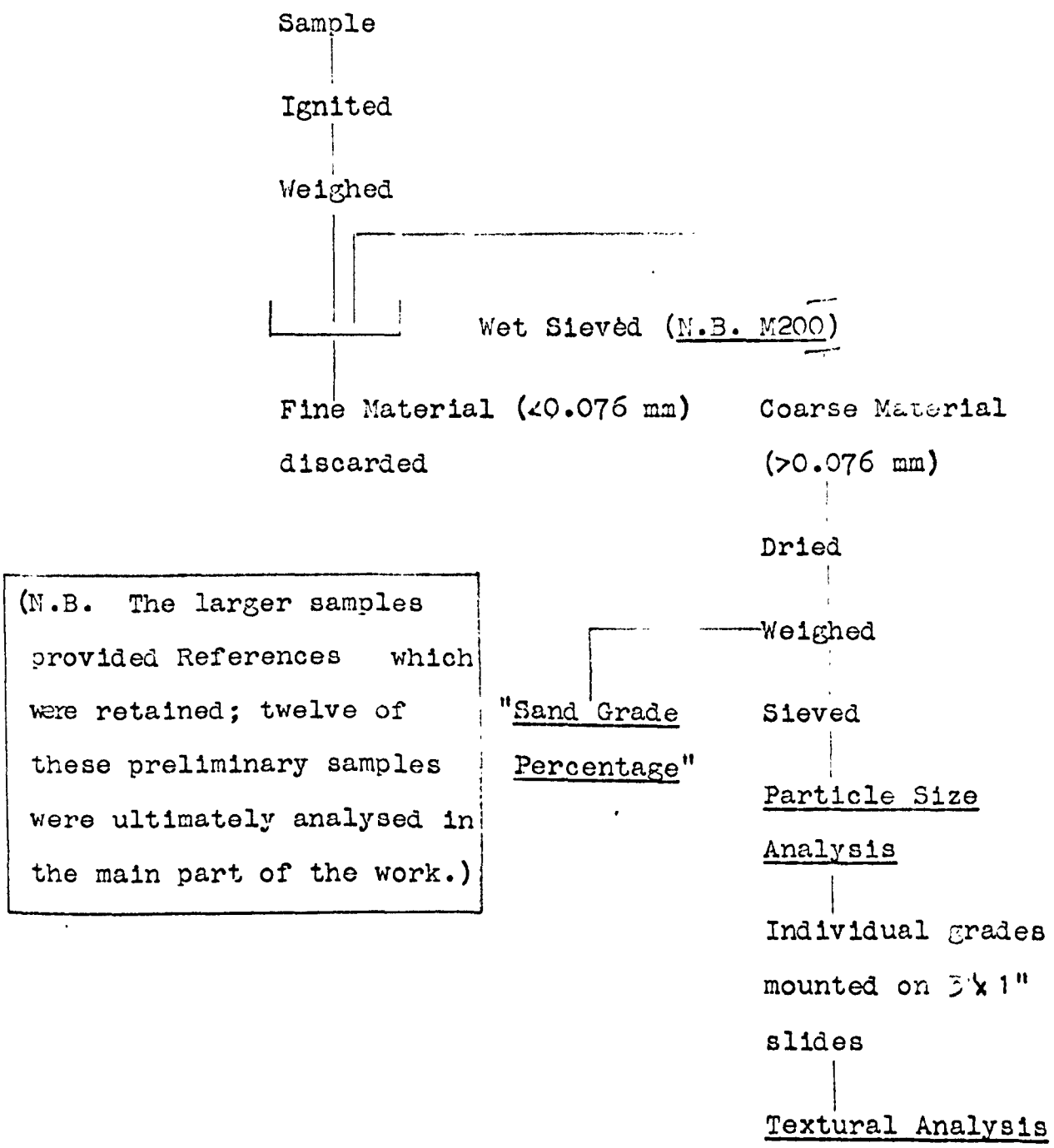


Figure iii. Preliminary Analyses - Flow Sheet.

Table 11. Preliminary Analyses - Table of Results.

Surface Ooze

Trip No. 1 - Localities on figure 1a.

Field Locality No.	Sample No.	Spot Sample No.	Water Depth (metres)	Sand Grade % (>0.076mm)	MD (mm)	SO	Roundness No.
S1	P1	1	3.0	3.2	0.121	1.36	-
S2	P2	2	6.0	2.4	0.127	1.41	-
S3	P3	3	2.5	4.1	0.116	1.27	-
S4	P4	4	17.0	0.7	0.124	1.35	-
S5	P5 (*2)	5	11.5	0.5	0.112	1.45	-
S6	P6	6	23.5	2.1	0.114	1.36	-
S7	P7 (*3)	7	-	1.0	0.107	1.39	-
S8	P8 (*1)	8	11.0	8.3	0.119	1.30	-
S9	P9	9	3.5	0.4	0.121	1.17	1.49
	P10 (*5)	10	3.5	11.9**	0.364**	3.04**	-
S10	P13	13	4.0	0.9	0.112	1.24	1.72
	P15	15	4.0	1.4	0.117	1.16	-
S11	P21	21	4.5	4.1	0.126	1.31	-
	P23	23	4.5	5.7	0.132	1.42	-
S12	P17	17	4.5	2.7	0.117	1.29	1.91
	P18	18	4.5	3.5	0.112	1.35	-
S13	P24	24	4.5	0.9	0.107	1.19	-
	P50 (*4)	50	4.5	2.6	0.111	1.35	-
S14	P43	43	5.0	2.3	0.122	1.26	1.53
	P20	20	5.0	1.7	0.131	1.26	-
S15	P22 (*8)	22	9.0	0.5	0.116	1.46	-
	P30	30	9.0	3.0	0.121	1.38	-

Table 11. Preliminary Analyses - Table of Results.

Surface Ooze

Trip No. 1 - Localities on figure 1a.

Field Locality No.	Sample No.	Spot Sample No.	Water Depth (metres)	Sand Grade % (>0.076mm)	MD (mm)	SO	Roundness No.
S16	P44 (*6)	44	4.5	10.4	0.148	1.31	-
	P36	36	4.5	8.5	0.137	1.27	-
S17	P42	42	4.5	1.2	0.121	1.42	-
S18	P53	53	7.0	0.5	0.118	1.36	-
	P41	41	7.0	0.2	-	-	-
S19	P27	27	17.0	42.6**	2.11**	4.03**	1.99**
	P48	48	17.0	27.3**	0.81**	3.45**	1.42**
S20	P40	40	-	3.8	0.097	1.37	-
	P48A (*7)	48A	-	1.1	0.104	1.48	-
S21	-	-	1.5 - 5.	No Samples were taken here.			
S22	P46	46	17.0	26.0	0.131	1.22	-
	P47	47	17.0	20.5	0.127	1.31	-
S23	P38	38	21.0	30.1	0.141	1.16	1.73
	P51	51	21.0	25.3	0.136	1.19	-
S24	P32	32	37.5	11.1	0.125	1.20	1.[illegible]
	P33	33	37.5	13.3	0.122	1.31	1.[illegible]

Table 11. Preliminary Analyses - Table of Results.

Clay

Trip No. 1 - Localities on figure 1a.

Field Locality No.	Sample No.	Spot Sample No.	Water Depth (metres)	Sand Grade % (>0.076mm)	MD (mm)	SO	Roundness No.
S11	P16	16	4.5	6.5	0.161	1.69	-
	P19 (*190)	19	4.5	1.2	0.183	1.81	-
S13	P29	29	4.5	3.5	0.419	1.83	-
	P25 (*204)	25	4.5	3.7	0.547	2.07	-
	P26	26	4.5	6.1	0.486	1.93	-
S14	P37	37	5.0	37.6	0.221	1.62	-
	P45	45	5.0	14.3	0.192	1.67	1.31
S16	P49	49	4.5	19.3	0.381	1.42	1.72
	P34 (*208)	34	4.5	54.2	0.618	1.54	-
S17	P35 (*207)	35	4.5	12.9	0.187	1.44	2.51

Appendix No. 4. Tables of Results from the Main Part of the Work.

Table iii; a. Flocculation and miscellaneous analyses.

b. Mechanical analyses.

c. Roundness analyses.

Notes on table iii:

Sample numbers are listed in order and divisions between facies are denoted by a gap in the tabulation, a full line, or a dashed line across the table; the major facies are started on new sheets.

⊟ : Data not available.

▭ : Data available but not measured for some reason.

Statistical Data. (table iiib)

All samples are bimodal unless specifically stated to be unimodal. Bimodal samples with more than 5% of each fraction are denoted by data from each fraction (group - see Chapter 13); when there is less than 5% of one fraction (generally coarse fraction) the data for that mode are not denoted. These are available but not measured (see above) because there was insufficient material in these cases.

There were three categories of unimodal material:

a. Material entirely greater than 0.064 mm (beach sands); in all these cases the data were derived from sieve analyses and are denoted in the appropriate column.

b. Material entirely smaller than 0.064 mm (silt or clay varves), these are denoted by Sedimentation Balance data.

c. Material both finer and coarser than 0.064 mm ("fine sandy lake deposits", fig. 62); in all these cases the data were derived by combining Sedimentation Balance and Emery Tube analyses; they are denoted in the Emery Tube column.

For convenience, the six samples (179 to 184) of pebbly layers in Late Glacial lacustrine material are each divided into two samples, the coarse fraction and the fine fraction; by definition, each of these is treated as unimodal.

An asterisk (*) placed by sieve data indicates that unusual gritty or coky material was present in that sample, which affected the coarse fraction data.

Lacustrine material with pebbles and/or coky fragments was not available in sufficient quantity to give a good representative sample of the coarse fractions; these are denoted none the less.

For purposes of comparison between Late Glacial and Post Glacial conditions in the lake Emery Tube data, which were used for all Post Glacial material, were used for Late Glacial material where practicable (less than 10% of coarse material was greater than Sieve Mesh 18); sieve analyses were used as well for <u>all</u> Late Glacial material with more than 5% greater than 0.064 mm. These latter are underlined for those samples in which both are denoted.

<u>Roundness Data.</u> (table iiic)

The <u>Weighted Mean</u> is referred to as the <u>Roundness Number</u> in the table.

*: Samples in which less than 200 pebbles were available for counting.

Present Day Deposits

Surface Ooze

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
1	40.5	.0078	21.9	-	-
2	10.5	.0055	21.1	-	-
3	25.5	.0055	22.1	-	-
4	65.5	.0078	14.3	-	-
5	4.0	.0039	16.5	-	-
6	>21.0	<.002	15.3	-	-
7	"negative"		12.0	-	-
8	>14.0	<.002	18.2	-	-
9	36.0	.0039	22.4	-	-
10	-	-	19.5	-	-
11	>19.0	<.002	12.4	-	5.3
12	14.5	.0039	11.1	-	6.3
13	>23.5	<.002	12.4	-	5.0
14	25.5	.0028	13.7	-	5.2
15	20.5	.0039	13.3	-	5.4
16	>18.5	<.002	12.1	-	6.2
17	26.5	.0039	10.0	-	6.4
18	>27.0	<.002	22.6	-	5.6
19	24.5	.0055	17.3	-	4.8

Surface Ooze

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
20	21.5	.0055	19.2	-	6.1
21	28.0	.0039	19.5	-	6.3
22	15.0	.0055	17.4	-	5.9
23	42.5	.0055	16.4	-	6.0
24	38.5	.011	14.2	-	4.5
25	47.0	.011	14.8	-	6.1
26	33.0	.0039	19.2	-	6.1
27	38.0	.0028	17.4	-	5.8
28	28.5	.0039	16.4	-	6.1
29	23.0	.0028	15.8	-	4.9
30	21.0	.011	19.4	-	6.0
31	32.5	.0028	23.6	-	6.8
32	33.0	.0039	25.5	-	6.6
33	22.5	.0055	24.0	-	6.6
34	43.0	.0055	23.3	-	6.2
35	31.0	.0078	21.2	-	7.0
36	8.0	.011	32.8	-	5.2
37	7.5	.0028	29.4	-	5.6
38	31.5	.0039	31.7	-	5.3

Table iiia. Flocculation and Miscellaneous Analyses - Results.

Post Glacial Deposits

Present Day - Near-Shore Silt

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
39			11.6	-	5.6
40			45.6	-	5.2
41			3.2	-	5.9

Gyttja

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
66	10.5	.0078	20.5	56.0	-
67	25.5	.0028	21.1	55.9	4.9
68	23.5	.0028	19.0	66.8	-
69	34.0	.0028	18.7	59.0	-
70	"negative"		20.4	-	5.4
71	>4.0	<.002	19.8	-	5.2
72	"negative"		18.3	64.8	6.0
73	"negative"		19.6	66.5	5.9
74	"negative"		21.2	-	5.4
75	9.0	.0039	16.9	40.1	-
76	"negative"		20.3	-	-
77	"negative"		21.4	-	-
78	"negative"		17.6	-	6.1
79	25.0	.0028	12.0	-	5.8
80	17.5	.0055	16.2	-	5.1
81	22.0	.0028	12.2	-	[illegible]
82	>17.0	<.002	14.8	-	5.8
83	>27.0	<.002	17.3	-	4.4
84	"negative"		17.2	-	5.5
85	18.0	.0028	13.8	77.6	6.4
86	>35.0	<.002	11.4	-	6.1

Table iiia. Flocculation and Miscellaneous Analyses - Results.

Early Post Glacial Deposits

Gyttja

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
87	-	-	18.3	81.5	6.8
88	10.5	.0055	28.6	63.7	-
89	>22.5	<.002	15.7	57.4	-
90	12.5	.0028	19.9	69.8	-
91	13.5	.0028	28.1	67.9	-
92	"negative"		25.1	-	5.5
93	"negative"		23.9	-	5.8
94	>11.5	<.002	37.6	66.4	5.7
95	>5.5	<.002	22.1	69.2	6.0
96	>1.0	<.002	18.0	-	5.4
97	44. 0	.0055	18.3	66.7	-
98	8.5	.0039	20.7	66.1	-
99	8.5	.0028	26.9	70.4	-
100	"negative"		21.1	-	5.5
101	14.0	.0039	18.1	-	5.5
102	>8.0	<.002	18.1	-	5.9
103	18.0	.0039	23.0	59.2	-
104	23.0	.0028	21.8	71.0	-
105	20.5	.0055	25.4	63.0	-

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
106	"negative"		21.9	-	5.2
107	"negative"		21.3	-	5.6
108	"negative"		19.0	66.7	5.5
109	"negative"		20.7	67.2	5.8
110	>19.5	<.002	20.6	-	5.5
111	22.0	.011	18.6	60.2	5.4
112	14.5	.0039	20.4	62.2	5.7
113	3.0	.0039	20.0	67.7	-
114	"negative"		19.6	-	5.7
115	3.0	.0039	16.8	-	5.8
116	>1.5	<.002	19.5	-	6.1
117	7.5	.0028	15.3	86.3	-
118	"negative"		22.4	-	5.7
119	"negative"		18.7	-	5.7
120	"negative"		15.5	67.9	5.6
121	"negative"		21.9	68.7	6.0
122	"negative"		18.5	-	5.0
123	12.5	.0055	13.2	54.1	-
124	13.5	.0055	14.3	59.7	-
125	"negative"		18.0	-	5.5

Table iiia. Flocculation and Miscellaneous Analyses - Results.

Early Post Glacial Deposits

Gyttja

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
126	12.5	.0028	17.3	-	5.9
127	>2.0	<.002	13.5	65.5	5.4
128	>17.5	<.002	16.1	64.1	5.5
129	>15.0	<.002	19.8	68.9	5.4
130	18.0	.0028	21.2	66.4	5.6
131	>22.0	<.002	20.4	67.3	5.5
132	>2.0	<.002	22.8	68.8	5.6
133	"negative"		20.9	66.9	5.3
134	>2.5	<.002	20.7	67.3	5.7
135	>10.0	<.002	14.9	65.0	5.3
136	"negative"		21.6	70.3	5.5

Black Ooze Bands - Fine Fraction only

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
140	-	-	14.3	-	-
141	-	-	11.7	-	-

Table IIIa. Flocculation and Miscellaneous Analyses - Results.

Late Glacial Deposits (*: Clay Band in Transitional Series)

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
143*			-	26.1	-
	Lacustrine Clays				
151			-	34.1	-
152			-	30.9	-
153			-	30.4	-
154			-	16.5	-
	Lacustrine Silts				
-			-	-	-
	Lacustrine Sands				
174			-	16.6	-
	"Rusty" Fluvio - Glacial Clays				
185			3.4	51.5	5.5
186			5.6	67.0	5.5
187			1.3	43.0	-
188			5.2	56.7	6.5
189			3.5	43.7	6.0

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
	"Smooth" Fluvio - Glacial Clays				
191			4.1	-	4.8
192			2.8	-	4.8
193			2.4	-	4.2
194			7.8	-	4.8
195			6.1	-	5.1
196			13.2	-	4.7
197			2.9	-	-
198			3.4	-	4.0
199			2.9	-	5.4
200			7.9	-	4.5
201			6.4	-	4.9
202			0.0	36.0	5.4
203			0.0	33.0	6.4
204			0.0	-	-
205			0.0	27.7	5.9
206			2.9	59.1	6.6
207			0.0	-	-
208			0.0	-	-

Table III a. Flocculation and Miscellaneous Analyses - Results.

Late Glacial Deposits

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			
	Fluvio - Glacial Sands				
209			3.4	-	-
210			50.0	-	-
	Deltaic Clays				
211			18.4	-	4.2
212			7.4	-	4.7
	Deltaic Silts				
213			11.3	-	4.0
214			14.7	-	4.2
215			14.2	-	4.1
216			4.5	-	4.5
217			9.9	-	3.9
	Boulder Clays				
218			3.2	-	4.8
219			2.2	-	-
220			1.5	-	-
221			3.2	-	4.7
222			3.0	-	5.0
223			4.2	-	5.0

SAMPLE NO.	FLOCCULATION DATA		ORGANIC CONTENT	WATER CONTENT	pH
	%	Size			

Table iiib. Mechanical Analyses - Table of Results.

Present Day Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
1	.0076	2.56	0.77	-	.093	1.37	1.01	.24	-	-	-	-	10.5	71.0	18.5	2.08	.081
2	.0055	2.20	0.89	-	-	-	-	-	-	-	-	-	0.9	78.1	21.0	2.20	-
3	.0044	2.12	1.00	-	-	-	-	-	-	-	-	-	1.3	74.7	24.0	2.23	-
4	.0034	2.66	1.10	-	-	-	-	-	-	-	-	-	3.0	61.5	35.5	2.33	-
5	.0041	2.27	1.11	-	-	-	-	-	.270*	3.12	1.61	0.31	13.0	65.0	22.0	2.09	.013
6	.0045	3.21	0.58	-	.140	1.26	1.16	.14	-	-	-	-	11.9	59.6	28.5	2.17	.032
7	.0066	-	-	-	-	-	-	-	-	-	-	-	1.4	61.6	37.0	2.36	-
8	.0043	2.50	0.49	-	-	-	-	-	-	-	-	-	0.5	67.0	32.5	2.32	-
9	.0021	4.94	0.66	-	.130	1.31	.12	.23	-	-	-	-	19.0	44.0	37.0	2.16	.019
10	.0020	3.05	1.09	-	.137	1.27	1.09	.22	-	-	-	-	12.5	44.6	42.9	2.30	.015
11	.0024	2.97	1.35	-	.144	1.62	1.43	.15	-	-	-	-	11.5	51.0	37.5	2.28	.017
12	.0022	4.01	1.04	-	.175	1.32	1.04	.25	-	-	-	-	38.0	32.0	30.0	1.93	.016
13	.0026	3.10	0.97	-	.175	1.37	1.04	.25	-	-	-	-	28.0	41.0	31.0	2.02	.019
14	.0018	2.88	1.05	-	.122	1.30	1.09	.31	-	-	-	-	8.0	48.0	44.0	2.38	.018
15	.0017	3.52	0.76	-	-	-	-	-	-	-	-	-	2.5	45.0	52.5	2.51	-
16	.0010	-	-	-	-	-	-	-	-	-	-	-	4.0	39.0	57.0	2.52	-
17	.0024	2.53	1.11	.29	-	-	-	-	-	-	-	-	3.0	52.0	45.0	2.42	-
18	.0047	3.27	0.50	-	.097	1.27	1.16	.23	-	-	-	-	8.2	59.3	32.5	2.24	.048
19	.0041	2.81	0.88	-	.099	1.34	1.29	.26	-	-	-	-	27.6	48.4	24.0	1.98	.041
20	.0040	3.16	1.06	-	-	-	-	-	-	-	-	-	3.5	62.5	34.0	2.31	-

Table iiib. Mechanical Analyses - Table of Results.

Present Day Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
21	.0040	2.05	1.38	-	-	-	-	-	-	-	-	-	1.8	78.2	20.0	2.18	-
22	.0048	2.09	1.09	-	-	-	-	-	-	-	-	-	2.0	78.5	19.5	2.17	-
23	.0040	2.29	1.20	-	-	-	-	-	-	-	-	-	2.7	67.8	29.5	2.26	-
24	.0050	2.35	0.88	-	-	-	-	-	-	-	-	-	4.1	71.9	24.0	2.20	-
25	.0037	3.21	0.71	-	.117	1.32	.08	.22	-	-	-	-	20.3	50.7	29.0	2.09	.032
26	.0042	2.24	1.37	-	-	-	-	-	-	-	-	-	3.5	75.0	21.5	2.18	-
27	.0047	3.03	0.65	-	-	-	-	-	-	-	-	-	4.6	62.9	32.5	2.28	-
28	.0034	3.13	0.75	-	-	-	-	-	1.22*	2.04	0.62	.26	9.4	56.6	34.0	2.25	.0023
29	.0048	2.32	0.60	-	.102	1.36	.02	.27	-	-	-	-	5.1	65.4	29.5	2.24	.047
30	.0068	1.66	0.64	.24	.150	1.56	.43	.29	-	-	-	-	10.6	74.9	14.5	2.04	.022
31	.0056	3.55	0.38	-	-	-	-	-	-	-	-	-	2.0	66.0	32.0	2.30	-
32	.0049	2.67	1.07	-	-	-	-	-	-	-	-	-	2.1	71.9	26.0	2.24	-
33	.0058	2.47	0.96	-	.092	1.16	.02	.17	-	-	-	-	19.3	65.7	15.0	1.96	.063
34	.0026	2.09	1.16	-	-	-	-	-	-	-	-	-	0.6	59.9	39.5	2.39	-
35	.0042	2.01	1.04	-	-	-	-	-	-	-	-	-	2.2	75.8	22.0	2.20	-
36	.0081	2.32	0.82	.30	.095	1.22	.08	.19	-	-	-	-	10.3	75.2	14.5	2.04	.085
37	.0075	2.49	0.80	.29	.106	1.25	.03	.27	-	-	-	-	12.9	69.1	18.0	2.05	.071
38	.0082	2.45	0.70	.28	.130	1.37	.08	.29	-	-	-	-	16.9	65.6	17.5	2.01	.063

Table iiib. Mechanical Analyses - Table of Results.

Present Day Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
39	(UNIMODAL)				.180	1.58	1.05	.19	-	-	-	-	90.1	9.9	0.0	1.10	
40	(UNIMODAL)				.0362	.370	.45	.24	-	-	-	-	20.0	70.0	10.0	1.90	
41	(UNIMODAL)				.070	1.30	1.16	.17	-	-	-	-	70.4	28.1	1.5	1.31	
42	(UNIMODAL)				-	-	-	-	.175	1.31	1.23	.14	100			1.0	
43	(UNIMODAL)				-	-	-	-	.440	1.49	1.10	.25	100			1.0	
44	(UNIMODAL)				-	-	-	-	.960	1.32	1.03	.21	100			1.0	
45	(UNIMODAL)				-	-	-	-	.900	1.28	1.07	.23	100			1.0	
46	(UNIMODAL)				-	-	-	-	1.08	1.36	1.14	.25	100			1.0	
47	(UNIMODAL)				-	-	-	-	0.57	2.78	1.02	.31	100			1.0	
48	(UNIMODAL)				-	-	-	-	.290	1.23	1.03	.26	100			1.0	
49	(UNIMODAL)				-	-	-	-	.960	1.54	1.05	0.29	100			1.0	
50	(UNIMODAL)				-	-	-	-	.665	1.46	1.02	.25	100			1.0	
51	(UNIMODAL)				-	-	-	-	.500	1.51	0.96	.28	100			1.0	
52	(UNIMODAL)				-	-	-	-	.616	1.24	1.10	.22	100			1.0	
53	(UNIMODAL)				-	-	-	-	2.82	1.23	1.03	.21	100			1.0	
54					-	-	-	-	Sample of large pebbles								
55	(UNIMODAL)				-	-	-	-	1.66	1.20	0.96	.22	100			1.0	
56	(UNIMODAL)				-	-	-	-	1.89	1.54	1.45	.20	100			1.0	
57	(UNIMODAL)				-	-	-	-	1.08	1.72	1.17	.23	100			1.0	
58	(UNIMODAL)				-	-	-	-	1.48	1.72	1.35	.21	100			1.0	
59	(UNIMODAL)				-	-	-	-	.360	1.31	0.99	.25	100			1.0	

Table iiib. Mechanical Analyses - Table of Results.

Present Day Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md/MD
60	(UNIMODAL)				-	-	-	-	1.73	1.17	1.02	.18	100			1.0	
61	(UNIMODAL)				-	-	-	-	.90	1.33	1.06	.25	100			1.0	
62	(UNIMODAL)				-	-	-	-	.90	1.70	0.96	.30	100			1.0	
63	(UNIMODAL)				-	-	-	-	.81	1.35	1.10	.22	100			1.0	
64	(UNIMODAL)				-	-	-	-	.43	1.26	1.00	.24	100			1.0	
65	(UNIMODAL)				-	-	-	-	.27	1.15	1.05	.23	100			1.0	

Table iiib. Mechanical Analyses - Table of Results.

Early Post Glacial Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
66	.0051	1.82	1.14	.28	140	1.37	1.20	.25	-	-	-	-	30.0	65.0	5.0	1.79	.041
67	.0043	2.52	0.94	-	155	1.29	1.11	.23	-	-	-	-	17.0	63.0	20.0	2.03	.037
68	.0048	2.75	1.04	-	-	-	-	-	-	-	-	-	2.5	70.0	27.5	2.25	-
69	.0028	2.20	1.39	-	-	-	-	-	-	-	-	-	4.0	60.0	36.0	2.32	-
70	.0052	2.06	1.15	.25	-	-	-	-	-	-	-	-	1.6	81.4	17.0	2.15	-
71	.0034	2.94	0.70	-	-	-	-	-	-	-	-	-	0.3	62.2	37.5	2.37	-
72	.0044	2.29	1.08	-	-	-	-	-	-	-	-	-	0.8	74.2	25.0	2.24	-
73	.0047	2.87	0.54	-	-	-	-	-	-	-	-	-	1.0	67.5	31.5	2.31	-
74	.0040	2.20	1.09	-	-	-	-	-	-	-	-	-	1.6	73.9	24.5	2.23	-
75	.0053	2.58	1.05	.31	170	1.40	1.07	.24	-	-	-	-	6.0	77.0	17.0	2.09	.031
76	.0042	3.60	0.65	-	-	-	-	-	-	-	-	-	4.2	58.8	37.0	2.33	-
77	.0060	2.17	0.92	.30	-	-	-	-	-	-	-	-	0.7	83.8	15.5	2.15	-
78	.0042	2.76	0.73	-	-	-	-	-	-	-	-	-	1.4	67.1	31.5	2.30	-
79	.0025	-	-	-	-	-	-	-	-	-	-	-	0.4	55.6	44.0	2.44	-
80	.0022	-	-	-	-	-	-	-	-	-	-	-	1.3	52.7	46.0	2.45	-
81	.0024	3.00	1.05	.31	135	1.30	1.07	.30	-	-	-	-	9.0	50.0	41.0	2.32	.020
82	.0019	3.40	1.22	-	-	-	-	-	-	-	-	-	4.0	47.0	49.0	2.47	-
83	.0014	3.65	1.20	-	-	-	-	-	-	-	-	-	1.0	43.0	56.0	2.55	-
84	.0017	2.64	1.05	-	-	-	-	-	-	-	-	-	1.0	46.0	53.0	2.53	-
85	.0032	2.99	1.05	-	160	1.42	1.06	.21	-	-	-	-	5.0	58.5	36.5	2.32	.020
86	.0021	2.57	1.50	.29	-	-	-	-	-	-	-	-	3.5	49.0	47.5	2.44	-
87	.0041	1.76	1.06	-	-	-	-	-	-	-	-	-	4.3	80.7	15.0	2.11	-

Table iiib. Mechanical Analyses - Table of Results.

Early Post Glacial Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
88	.0048	?.02	1.29	.29	.130	1.37	1.00	.23	-	-	-	-	37.0	56.0	7.0	1.73	.037
89	.0044	?.92	0.99	-	.117	1.28	1.45	.24	-	-	-	-	8.0	65.5	26.5	2.16	.042
90	.0063	2.68	0.86	-	-	-	-	-	-	-	-	-	2.5	74.0	23.5	2.20	-
91	.0044	?.76	1.22	-	-	-	-	-	-	-	-	-	3.5	69.0	27.5	2.24	-
92	.0046	?.36	0.85	-	-	-	-	-	-	-	-	-	1.3	71.7	27.0	2.26	-
93	.0036	?.57	0.86	-	-	-	-	-	-	-	-	-	0.6	66.9	32.5	2.32	-
94	.0030	-	-	-	-	-	-	-	-	-	-	-	1.4	57.1	41.5	2.40	-
95	.0039	?.44	0.88	-	-	-	-	-	-	-	-	-	1.9	68.1	30.0	2.28	-
96	.0028	-	-	-	-	-	-	-	-	-	-	-	2.5	49.0	48.5	2.46	-
97	.0033	?.50	1.19	-	-	-	-	-	-	-	-	-	1.5	63.5	35.0	2.32	-
98	.0040	?.80	0.96	-	-	-	-	-	-	-	-	-	1.5	63.5	35.0	2.32	-
99	.0054	?.33	1.00	-	-	-	-	-	-	-	-	-	3.0	77.0	20.0	2.17	-
100	.0045	3.54	0.89	-	-	-	-	-	-	-	-	-	1.9	67.1	31.0	2.29	-
101	.0031	-	-	-	-	-	-	-	-	-	-	-	0.2	65.8	34.0	2.34	-
102	.0028	-	-	-	-	-	-	-	-	-	-	-	2.4	56.6	41.0	2.39	-
103	.0046	2.54	1.34	.29	.130	1.40	1.27	.21	-	-	-	-	7.0	68.0	25.0	2.20	.040
104	.0045	2.54	1.03	-	-	-	-	-	-	-	-	-	1.5	70.0	28.5	2.27	-
105	.0050	?.29	1.16	-	-	-	-	-	-	-	-	-	1.5	78.5	20.5	2.17	-
106	.0035	3.18	0.74	-	-	-	-	-	-	-	-	-	1.1	60.9	38.0	2.37	-
107	.0023	-	-	-	-	-	-	-	-	-	-	-	0.1	53.9	46.0	2.46	-
108	.0043	2.11	0.96	-	-	-	-	-	-	-	-	-	0.1	75.9	24.0	2.24	-

Table iiib. Mechanical Analyses - Table of Results.

Early Post Glacial Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
109	.0043	2.89	0.65	-	-	-	-	-	-	-	-	-	1.6	66.4	32.0	2.30	-
110	.0018	-	-	-	-	-	-	-	-	-	-	-	0.6	47.4	52.0	2.51	-
111	.0053	1.54	1.22	.17	-	-	-	-	-	-	-	-	3.5	88.5	8.0	2.05	-
112	.0040	2.41	0.87	-	-	-	-	-	-	-	-	-	1.0	69.0	30.0	2.29	-
113	.0040	1.86	1.10	.26	-	-	-	-	-	-	-	-	2.0	78.0	20.0	2.17	-
114	.0036	2.13	1.14	-	-	-	-	-	-	-	-	-	1.2	71.8	27.0	2.26	-
115	.0030	-	-	-	-	-	-	-	-	-	-	-	0.5	60.5	39.0	2.38	-
116	.0026	-	-	-	-	-	-	-	-	-	-	-	3.6	56.4	40.0	2.36	-
117	.0032	2.45	1.38	-	-	-	-	-	-	-	-	-	2.5	63.5	34.0	2.32	-
118	.0045	3.20	0.47	-	-	-	-	-	-	-	-	-	0.9	64.6	34.5	2.34	-
119	.0034	2.24	0.85	-	-	-	-	-	-	-	-	-	0.5	66.0	33.5	2.33	-
120	.0029	-	-	-	-	-	-	-	-	-	-	-	0.5	60.0	39.5	2.39	-
121	.0068	2.15	0.73	.23	-	-	-	-	-	-	-	-	1.3	77.7	21.0	2.20	-
122	.0054	2.15	0.77	-	-	-	-	-	-	-	-	-	0.7	76.8	22.5	2.22	-
123	.0049	2.50	0.86	-	-	-	-	-	-	-	-	-	2.5	70.0	27.5	2.24	-
124	.0035	2.09	1.10	-	-	-	-	-	-	-	-	-	0.5	70.5	29.0	2.28	-
125	.0028	-	-	-	-	-	-	-	-	-	-	-	0.2	59.8	40.0	2.40	-
126	.0018	-	-	-	-	-	-	-	-	-	-	-	0.5	48.5	57.0	2.51	-
127	.0043	3.04	0.84	-	-	-	-	-	-	-	-	-	1.3	68.2	30.5	2.29	-
128	.0039	2.49	1.11	-	-	-	-	-	-	-	-	-	1.5	70.0	28.5	2.27	-

Table iiib. Mechanical Analyses - Table of Results.

Early Post Glacial Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
129.	.0046	3.00	0.83	-	-	-	-	-	-	-	-	-	0.5	69.5	30.0	2.29	-
130.	.0040	2.27	1.05	-	-	-	-	-	-	-	-	-	1.0	73.0	26.0	2.25	-
131.	.0043	2.90	0.71	-	-	-	-	-	-	-	-	-	1.0	67.0	32.0	2.31	-
132.	.0044	2.24	0.89	-	-	-	-	-	-	-	-	-	1.0	73.0	26.0	2.25	-
133.	.0044	2.47	1.02	-	-	-	-	-	-	-	-	-	0.4	73.1	26.5	2.26	-
134.	.0050	2.30	0.68	-	-	-	-	-	-	-	-	-	1.6	72.4	26.0	2.24	-
135.	.0026	-	-	-	-	-	-	-	-	-	-	-	0.2	56.8	43.0	2.43	-
136.	.0060	2.28	0.90	.25	-	-	-	-	-	-	-	-	0.8	78.7	20.5	2.20	-
137.	(UNIMODAL)				.0409	.060	0.12	-	-	-	-	-	40.6	31.4	28.0	1.87	
138.	(UNIMODAL)				.0147	.910	0.43	-	-	-	-	-	26.0	45.5	28.5	2.02	
139.	(UNIMODAL)				.0496	.960	0.14	-	-	-	-	-	41.3	35.2	23.5	1.82	
140.	.0065	2.40	0.92	.24	-	-	-	-	13.5*	1.57*	0.76	.11	12.5	69.5	18.0	2.06	.0004
141.	.0047	3.81	0.61	-	-	-	-	-	10.0*	1.35*	0.79	.12	17.6	54.4	28.0	2.10	.0004
142.	.0013	-	-	-	(UNIMODAL)								0.0	31.0	69.0	2.69	
143.	.0014	-	-	-	(UNIMODAL)								0.0	41.0	59.0	2.59	
144.	.0012	-	-	-	(UNIMODAL)								0.0	33.5	66.5	2.67	

Table iiib. Mechanical Analyses - Table of Results.

Late Glacial Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
145	.0028	1.70	0.71	-	(UNIMODAL)				(see Sample No. 179)				56.3	43.7	2.44		.0017
146	.0021	2.05	1.10	-	(UNIMODAL)				(see Sample No. 180)				55.4	44.6	2.45		.0007
147	.0019	2.46	0.92	-	(UNIMODAL)								0.0	50.0	50.0	2.50	
148	.0014	2.40	1.07	-	(UNIMODAL)				(see Sample No. 181)				40.0	60.0	2.60		.0005
149	.0012	-	-	-	(UNIMODAL)								0.0	31.0	69.0	2.69	
150	.0008	-	-	-	(UNIMODAL)								0.0	24.5	75.5	2.76	
151	.0011	-	-	-	(UNIMODAL)								0.0	32.5	67.5	2.67	
152	.0011	-	-	-	(UNIMODAL)								0.0	32.5	67.5	2.67	
153	.0009	-	-	-	(UNIMODAL)								0.0	24.0	76.0	2.76	
154	.0042	2.48	0.89	-	(UNIMODAL)				(see Sample No. 182)				69.6	30.4	2.30		.0016
155	.0019	-	-	-	(UNIMODAL)								0.0	49.0	51.0	2.51	
156	.0011	-	-	-	(UNIMODAL)								0.0	29.0	71.0	2.71	
157	.0010	-	-	-	(UNIMODAL)								0.0	22.0	78.0	2.78	
158	.0009	-	-	-	(UNIMODAL)								0.0	19.0	81.0	2.81	
159	.0009	-	-	-	(UNIMODAL)								0.0	24.0	76.0	2.76	
160	.0009	-	-	-	(UNIMODAL)								0.0	27.5	72.5	2.72	
161	.0063	1.90	0.77	.25	(UNIMODAL)				(see Sample No. 183)				84.4	15.6	2.16		.0004
162	.0059	1.84	0.88	.24	(UNIMODAL)								0.0	33.5	16.5	2.16	
163	.0012	-	-	-	(UNIMODAL)								0.0	24.5	75.5	2.75	
164	.0009	-	-	-	(UNIMODAL)								0.0	22.0	78.0	2.78	
165	.0008	-	-	-	(UNIMODAL)								0.0	21.0	79.0	2.79	

Table iiib. Mechanical Analyses - Table of Results.

Late Glacial Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
166	.0031	2.84	0.65	-	(UNIMODAL)								0.0	61.0	39.0	2.39	
167	.0044	3.55	0.34	-	(UNIMODAL)								0.0	63.0	37.0	2.37	
168	.0048	3.19	0.48	-	(UNIMODAL)								0.0	67.0	33.0	2.33	
169	.0065	2.62	0.58	-	(UNIMODAL)								0.0	74.5	25.5	2.25	
170	.0020	-	-	-	(UNIMODAL)								0.0	50.0	50.0	2.50	
171	.0088	3.83	0.26	-	(UNIMODAL)								0.0	72.0	28.0	2.28	
172	.0065	3.48	0.35	-	(UNIMODAL)				(see Sample No. 184)				69.2	30.8	2.40		.0002
173	.0073	2.24	0.63	.23	(UNIMODAL)								0.0	78.0	22.0	2.22	
174	(UNIMODAL)				.017	2.25	0.89	.26	-	-	-	-	10.5	77.5	12.0	2.01	
175	.0059	1.63	1.22	.24	.103	1.13	1.02	.22	.092	1.13	1.04	.22	14.7	69.3	16.0	2.01	.064
176	.0099	2.53	0.77	.22	.106	1.17	1.10	.21	.095	1.15	1.01	.21	26.0	62.0	12.0	1.87	.104
177	.0103	3.39	0.37	-	.108	1.17	1.07	.23	.095	1.15	1.01	.21	39.0	45.0	16.0	1.75	.108
178	(UNIMODAL)				.015	2.16	0.57	.23	-	-	-	-	5.4	80.1	14.5	2.09	
179	(see Sample 45)				-	-	-	-	1.41	2.44	1.04	.28	100			1.0	.0017
180	(see Sample 46)				-	-	-	-	2.65	3.16	0.87	-	100			1.0	.0007
181	(see Sample 48)				-	-	-	-	1.50	1.78	0.77	.07	100			1.0	.0003
182	(see Sample 54)				-	-	-	-	2.55	2.95	0.82	.27	100			1.0	.0015
183	(see Sample 61)				-	-	-	-	16.0	1.60	0.61	.23	100			1.0	.0004
184	(see Sample 72)				-	-	-	-	27.0	2.08	0.39	.19	100			1.0	.0002

Table iiib. Mechanical Analyses - Table of Results.
Late Glacial Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction												
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø	Sand %	Silt %	Clay %	Mean	Md / MD
185	.0028	2.05	1.05	.29	.170	1.67	1.35	.24	.167	1.71	1.38	.24	34.0	44.0	22.0	1.88	.016
186	.0009	-	-	-	.175	1.53	1.16	.23	.158	1.49	1.08	.20	0.0	30.0	60.0	2.50	.0064
187	.0026	-	-	-	-	-	-	-	.135	1.58	1.60	.16	26.0	46.0	28.0	2.03	.016
188	.0016	2.64	1.12	-	-	-	-	-	-	-	-	-	1.5	44.5	54.0	2.53	-
189	.0025	3.24	0.94	-	-	-	-	-	.440	1.88	0.89	.29	18.0	41.0	41.0	2.23	.007
190	.0017	-	-	-	-	-	-	-	-	-	-	-	1.5	44.0	54.5	2.53	-
191	.0093	2.77	1.23	-	-	-	-	-	.375	2.62	1.23	.30	30.2	54.8	15.0	1.85	.020
192	.0045	3.37	0.79	-	-	-	-	-	.740	2.07	1.38	.23	71.8	20.2	8.0	1.36	.005
193	.0100	2.89	0.73	.29	-	-	-	-	.250	1.42	1.14	.15	77.5	18.5	4.0	1.27	.033
194	.0096	2.66	0.81	.30	-	-	-	-	.667	2.48	1.45	.25	57.4	36.6	6.0	1.49	.012
195	.0113	2.24	0.83	.28	-	-	-	-	1.58	2.03	1.00	.25	73.6	23.9	2.5	1.29	.006
196	.0029	1.74	1.23	-	.125	1.99	1.46	.31	.111	1.87	1.51	0.31	14.7	60.8	24.5	2.10	.023
197	-	-	-	-	-	-	-	-	2.40	2.69	1.02	.31	97.8	1.7	0.5	1.03	-
198	.0025	-	-	-	-	-	-	-	1.75	2.57	1.02	.26	72.4	13.6	14.0	1.42	.001
199	.0093	3.62	0.57	-	.170	1.62	1.20	.25	.152	1.65	1.21	.25	27.3	54.7	18.0	1.91	.055
200	.0120	3.03	0.87	.30	-	-	-	-	.433	1.40	0.99	.19	58.2	17.3	14.5	1.46	.023
201	.0088	3.40	0.57	-	-	-	-	-	.240	2.20	1.42	.18	32.6	57.4	16.0	1.83	.030
202	.0021	3.28	0.37	-	-	-	-	-	-	-	-	-	4.5	47.5	48.0	2.43	-
203	.0024	1.34	.18	.22	-	-	-	-	-	-	-	-	4.5	70.5	25.0	2.19	-
204	.0020	-	-	-	-	-	-	-	-	-	-	-	4.2	46.8	49.0	2.45	-
205	.0042	2.04	0.85	.29	-	-	-	-	-	-	-	-	0.5	74.5	25.0	2.26	-

Table iiib. Mechanical Analyses - Table of Results.

Late Glacial Deposits

SAMPLE NO.	STATISTICAL DATA												GRADE DATA				RATIO
	Fine Fraction				Coarse Fraction								Sand %	Silt %	Clay %	Mean	Md / MD
	Sed. Bal.				Emery Tube				Sieves								
	Md	So	Sk	kø	MD	SO	SK	Kø	MD	SO	SK	Kø					
206	.0005	-	-	-	-	-	-	-	-	-	-	-	4.5	35.0	60.5	2.55	-
207	.0037	2.31	1.10	-	178	1.52	1.11	.26	.156	1.47	1.08	.26	4.5	63.0	22.5	2.08	.020
208	.0009	-	-	-	-	-	-	-	.500	1.67	1.01	.25	67.1	4.9	28.0	1.61	.0014
209	-	-	-	-	-	-	-	-	.850	1.38	1.19	.17	96.5	3.5	0.0	1.04	-
210	-	-	-	-	-	-	-	-	.535	1.44	0.97	.24	98.1	1.9	0.0	1.02	-
211	.0052	3.08	0.79	-	-	-	-	-	-	-	-	-	2.5	68.0	29.5	2.27	-
212	.0050	4.69	0.37	-	102	1.54	1.18	.29	.097	1.56	1.21	.30	20.2	49.8	30.0	2.10	.049
213	.0095	2.73	1.01	.31	170	1.50	1.12	.30	.151	1.43	1.09	.28	41.7	50.8	7.5	1.66	.056
214	.0145	3.05	0.82	.31	098	1.14	1.07	.16	.095	1.11	1.09	.18	20.1	73.9	6.0	1.86	.148
215	.0138	3.41	0.71	.31	116	1.50	1.64	.24	.109	1.37	1.51	.24	21.5	65.0	13.5	1.92	.120
216	.0163	3.32	0.49	.27	-	-	-	-	.820	2.18	0.89	.26	80.8	15.2	4.0	1.23	.017
217	.0052	2.10	0.94	-	240	1.91	0.84	.27	.217	1.85	0.77	.29	56.1	37.9	6.0	1.40	.022
218	.0094	2.91	0.80	.29	-	-	-	-	(Polymodal)				46.9	42.1	11.0	1.64	-
219	.0150	2.46	0.73	.21	-	-	-	-	1.25	3.26	1.01	.30	72.9	25.1	2.0	1.29	.010
220	.0114	2.46	0.51	.26	-	-	-	-	2.65	3.20	0.84	.31	90.6	7.9	1.5	1.11	.003
221	.0035	3.23	0.85	-	-	-	-	-	2.15	3.98	0.73	.31	39.1	35.9	25.0	1.96	.001
222	.0059	2.96	0.69	-	-	-	-	-	2.90	3.45	0.88	0.31	76.0	18.0	6.0	1.30	.001
223	.0082	3.13	0.74	-	-	-	-	-	3.75	3.41	0.81	.30	75.2	22.3	2.5	1.27	.001

Table iiic. Roundness Analyses - Table of Results.

Post Glacial Deposits

Beach Deposits

SAMPLE NO.	ROUNDNESS NO.
42	1.96*
43	1.96*
44	2.24
45	1.80*
46	2.77*
47	2.10
48	2.80*
49	2.52*
50	2.87
51	2.59*
52	3.83*
53	3.03
54	3.35*
55	2.79*
56	2.53
57	2.54
58	2.57
59	3.14*
60	3.12*
61	2.53*
62	2.63*
63	2.52*
64	2.34*
65	1.98*

SAMPLE NO.	ROUNDNESS NO.
Gritty Material in Surface Ooze	
28	2.50*
Black Ooze Bands in Gyttja	
140 (Coky fragments)	1.00*
141 (Coky fragments -	1.00*
and pebbles) -	1.50*

Table iiic. Roundness Analyses - Table of Results.

Late Glacial Deposits

SAMPLE NO.	ROUNDNESS NO.
Pebble Layers in Lacustrine Clays and Silts	
179	1.82*
180	1.80*
181	1.98*
182	1.59*
183	2.10*
184	2.00*
Pebble Fraction in Fluvio - Glacial Clays	
185	1.50*
187	1.28*
189	1.00*
191	1.82*
192	2.62*
193	2.62*
194	2.31*
195	2.72*
196	2.27*
197	2.27
198	2.35*
199	2.86*
200	2.79*
201	2.66*
202	1.85
208	2.32*
Fluvio - Glacial Sands	
209	2.73*
210	1.84*
Pebble Fraction in Deltaic Silts	
216	2.41*
Pebble Fraction in Boulder Clays	
218	1.94*
219	1.95*
220	2.26*
221	2.55*
222	1.84*
223	2.31*

Appendix No. 5. Standard Thermograms of Pure Minerals. (table iv)

The pure minerals are listed with the original source where known and the institutions or companies that provided them to this department. The chemical formulae, where noted, apply to the end members of the groups of the groups concerned. The numbers referred to appear in the American Petroleum Institute, Clay Minerals Standards, Project No. 49 (A.P.I. No.), a publication which gives details of the minerals and their properties, including differential thermal properties.

Also listed are the different conditions of preparation and analysis of each mineral. The thermograms are shown on figure iv.

Table iv. List of Pure Minerals for D. T. Apparatus.

(Thermograms on figure iv)

Group	Mineral (Formula)	Source (A.P.I.No.)	Provisor	Conditions: Preparation, Analysis
SILICA	Quartz SiO2		U.C.L. Mineral Collection	Water - Air Calgon- Air
KANDITE	Kaolinite Al2O3.2SiO2.2H2O	"Supreme"	English Clay, Lovering, Pochin and Co. Ltd.	Water - Air Calgon- Air
		"No. 2". Birch Pit, Macon, Georgia, USA.	School of Agiculture, Cambridge University.	Water - Air
		"No. 4"	Dept. of Geology, Leicester University.	Water - Air
		"Superfine Molochite" (Inert)	English Clay, Lovering, Pochin and Co. Ltd.	Precalcined 1800° C for 48 hours
	Halloysite Al2O3.2SiO2.4H2O	"No. 12". North Gardiner Mine, Bedford, Huron	School of Agriculture, Cambridge University.	Water - Air
		"No. 29"	Dept. of Geology, Leicester University.	Water - Air Calgon- Air
	Dickite Al2O3.2SiO2.2H2O	"No. 15"	Dept. of Geology, Leicester University.	Water - Air Calgon- Air
		"Type". Bundorgan, Anglesey.	U.C.L. Mineral Collection	Water - Air

Table iv. List of Pure Minerals for D. T. Apparatus.

(Thermograms on figure iv)

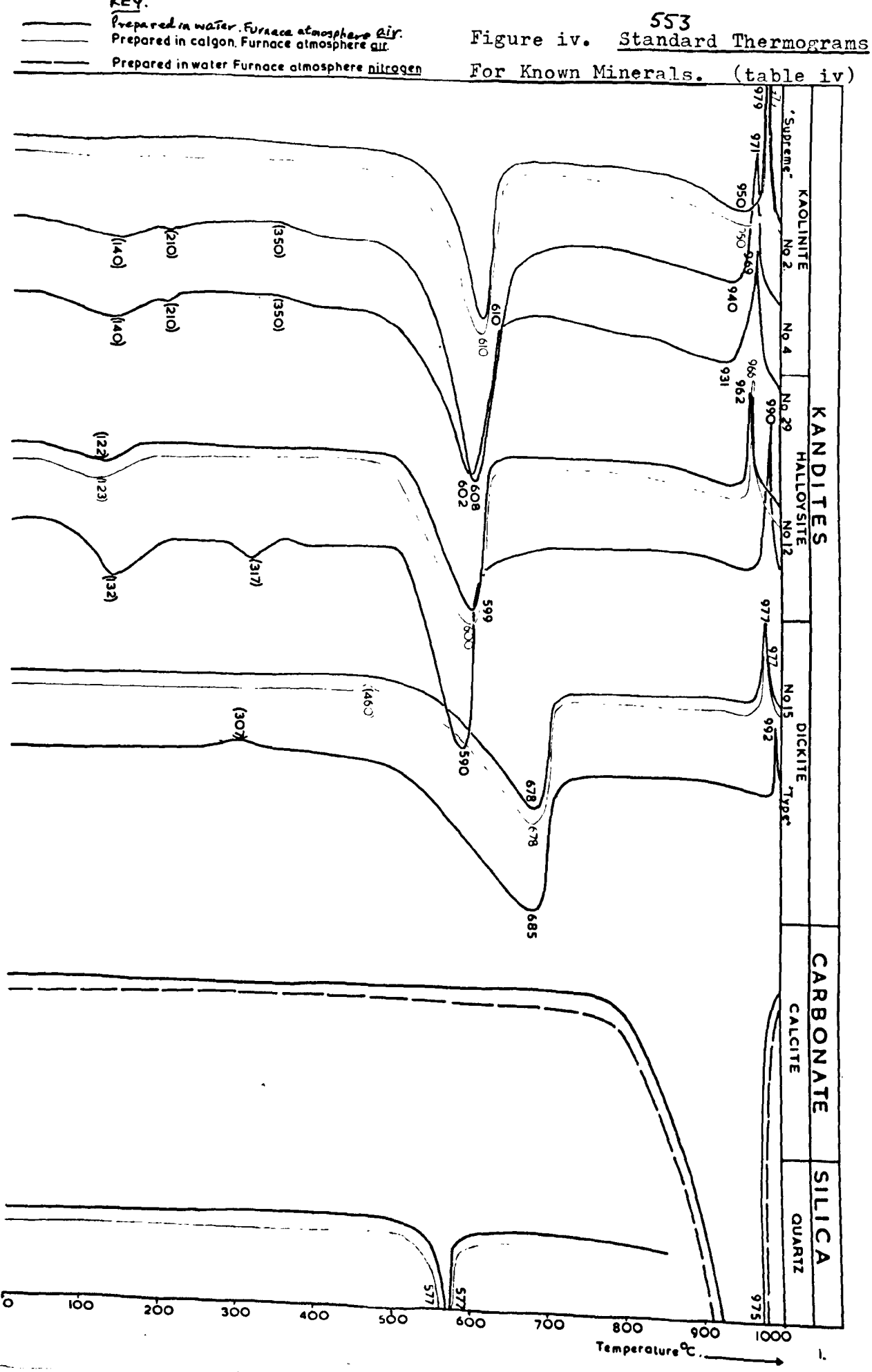
Group	Mineral (Formula)	Source (A.P.I.No.)	Provisor	Conditions: Preparation, Analysis
SMECTITE	Montmorillonite (Al3.33,MgO.67) Si8.08(OH)4	"No. 26". Clay Spur, Wyoming. (Bentonite)	School of Agriculture Cambridge University.	Water - Air Calgon- Air Water-Nitrogen
		"No. 27"	Dept. of Geology, Leicester University.	Water - Air
	Bentonite	"Genuine Wyoming"	F.W. Berk and Co. Ltd.	Water - Air Calgon- Air Water-Nitrogen
		"North African"	F.W. Berk and Co. Ltd.	Water - Air
		"Italian"	F.W. Berk and Co. Ltd.	Water - Air
	"Metabentonite"	"No. 38"	Dept. of Geology, Leicester University.	Water - Air Calgon- Air
CLAY MICAS	Illite (Hydramica)	Fithian, Illinois. (N.B. Pure)	Geological Survey and Museum; Mineral Inventory:MI27986	Water-Nitrogen
		"No. 36". Morris, Illinois.	School of Agriculture Cambridge University.	Water - Air Calgon- Air Water-Nitrogen
		Fithian, Illinois. (N.B. Impure)	Geological Survey and Museum; Mineral Inventory:MI29668	Water-Nitrogen
MICA	Muscovite		U.C.L. Mineral Collection	Water - Air

Table iv. List of Pure Minerals for D. T. Apparatus.

(Thermograms on figure iv)

Group	Mineral (Formula)	Source (A.P.I.No.)	Provisor	Conditions: Preparation, Analysis
MICA	Hydrobiotite		U.C.L. Mineral Collection	Water - Air
CARBONATE	Calcite $CaCO_3$		U.C.L. Mineral Collection	Water - Air
OXIDES	Goethite $\alpha FeO-OH$		U.C.L. Mineral Collection	Water - Air Calcon- Air
	Bauxite (General Al - Oxide)		U.C.L. Mineral Collection	Water - Air Calcon- Air
	Diaspore $\alpha AlO-OH$		U.C.L. Mineral Collection	Water - Air
PHOSPHATE	Vivianite $Fe_3(PO_4).8H_2O$	Windermere; Lake Sediments		Water - Air

Figure iv. Standard Thermograms For Known Minerals. (table iv)



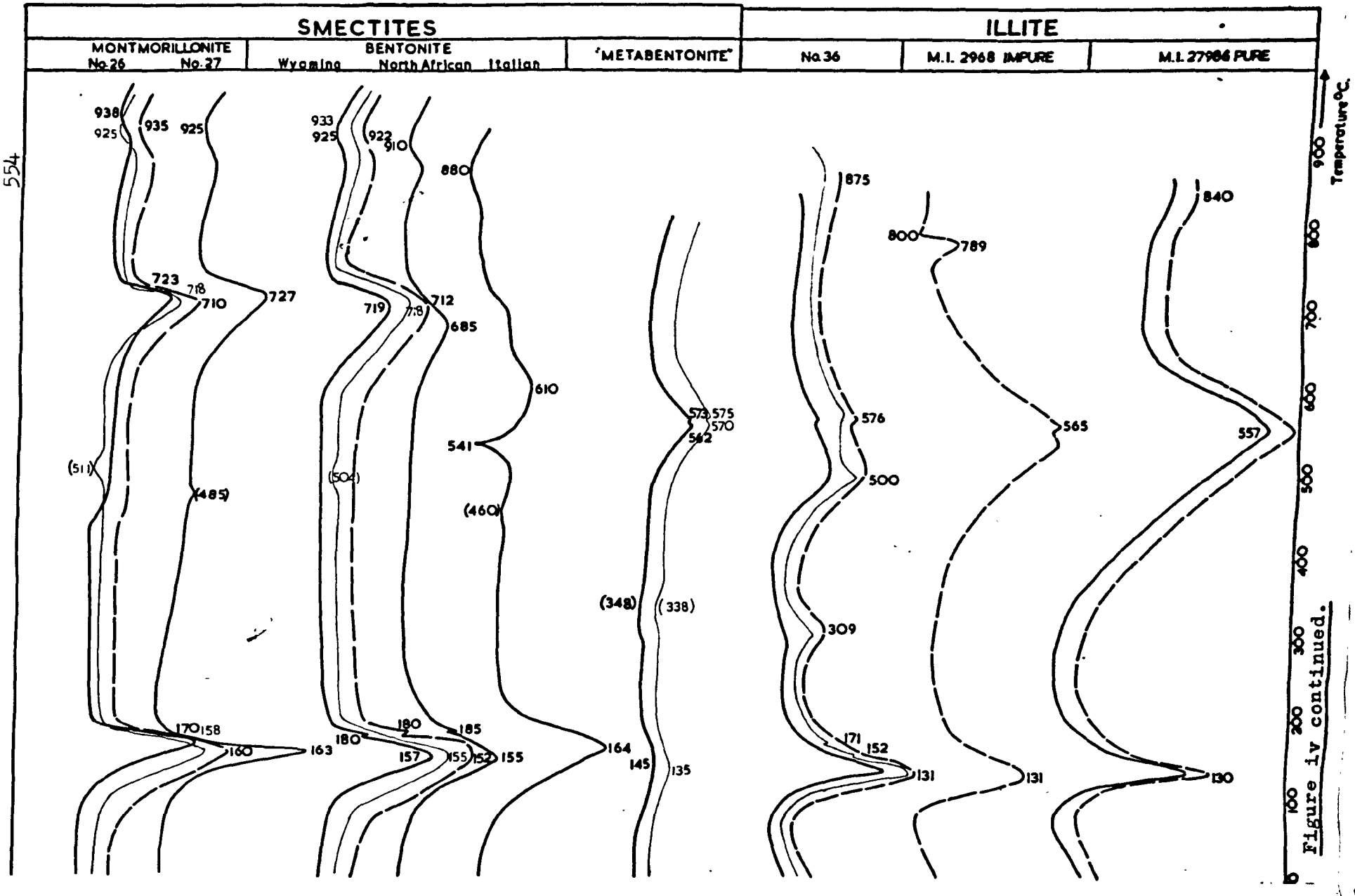


Figure 1v continued.

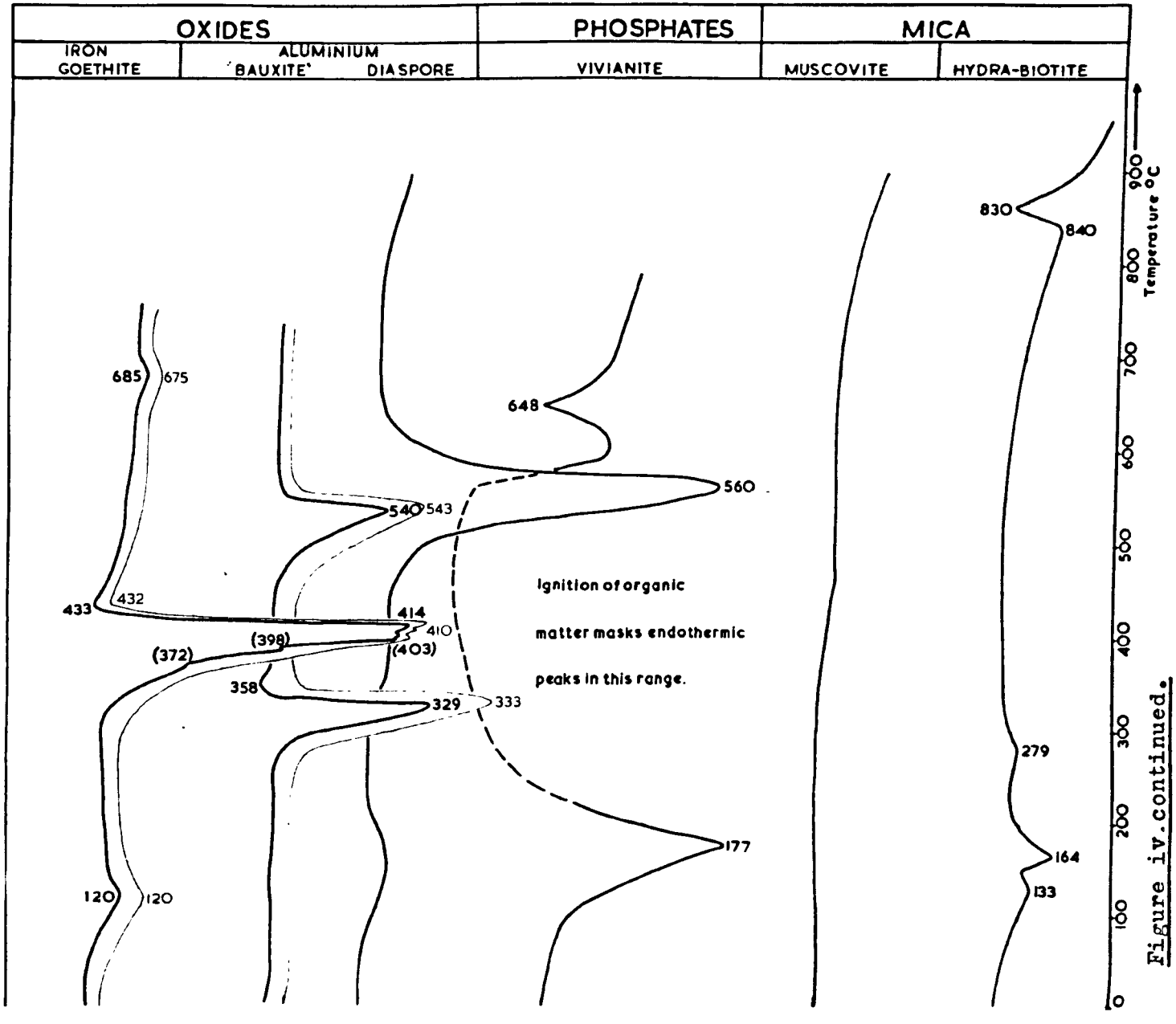


Figure iv. continued.

PULLOUT

330,000m.E.

340,000m.E.

510,000m.N.

500,000m.N.

490,000m.N.

Grasmere.

Rydal Water.

Great Langdale Beck.

Elter Water.

River Brathay.

River Rothay.

AMBLESIDE.

Stock Ghyll.

Hagg Ghyll.

TROUTBECK PARK.

ROMAN FORT.

WATERHEAD.

STEEP SLOPES.

Troutbeck.

Brathay Delta.

Hol Beck.

NORTH BASIN OF WINDERMERE

67M

60M

40M

20M

Slack Wood Beck.

Troutbeck Delta.

Drumlins.

HAWKSHEAD.

CLAIFE HEIGHTS

Esthwaite Water.

BOWNESS ON WINDERMERE.

BELLE ISLE.

FERRY HOUSE.

THRESHOLD

COCKSHOTT POINT.

SAWREY.

Cunsey Beck.

SOUTH BASIN

LAKESIDE 1½ miles.

NEWBY BRIDGE 2½ miles.

Figure 4. Catchment Area of Windermere, Showing Features Referred to in Chapter 1.

Key.

20M — Depth of water in Windermere, (Metres).

— — — Watershed.

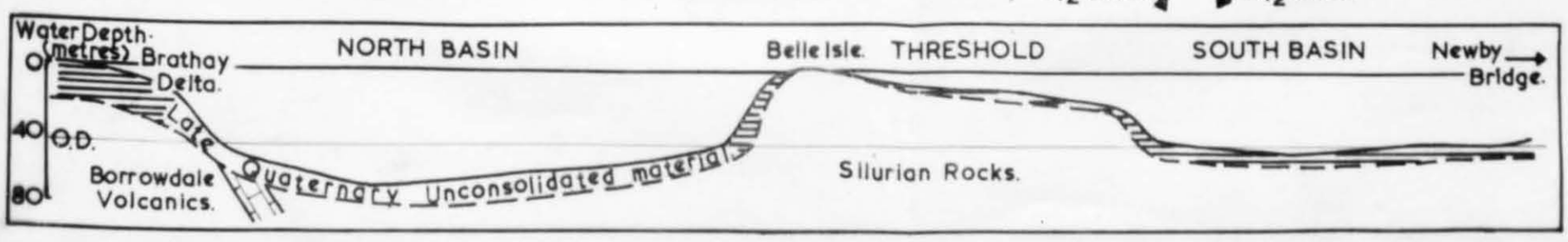
Geomorphological observations.

- 5' platform.
- 25' platform.
- Beginning of steep slope up from platform feature.
- Striated pavement.
- Direction of ice-flow.
- Land over 500'.
- Coniston Limestone, lying unconformably on Borrowdale Volcanics to the north; overlain conformably by Silurian rocks to the south.

N

Scale.

0 1 2 miles.



a. Surface Sampling Localities.

b. Core Sampling Localities.

c. Shoreline Sampling Localities.

d. Pink's Catchment Area Samples.

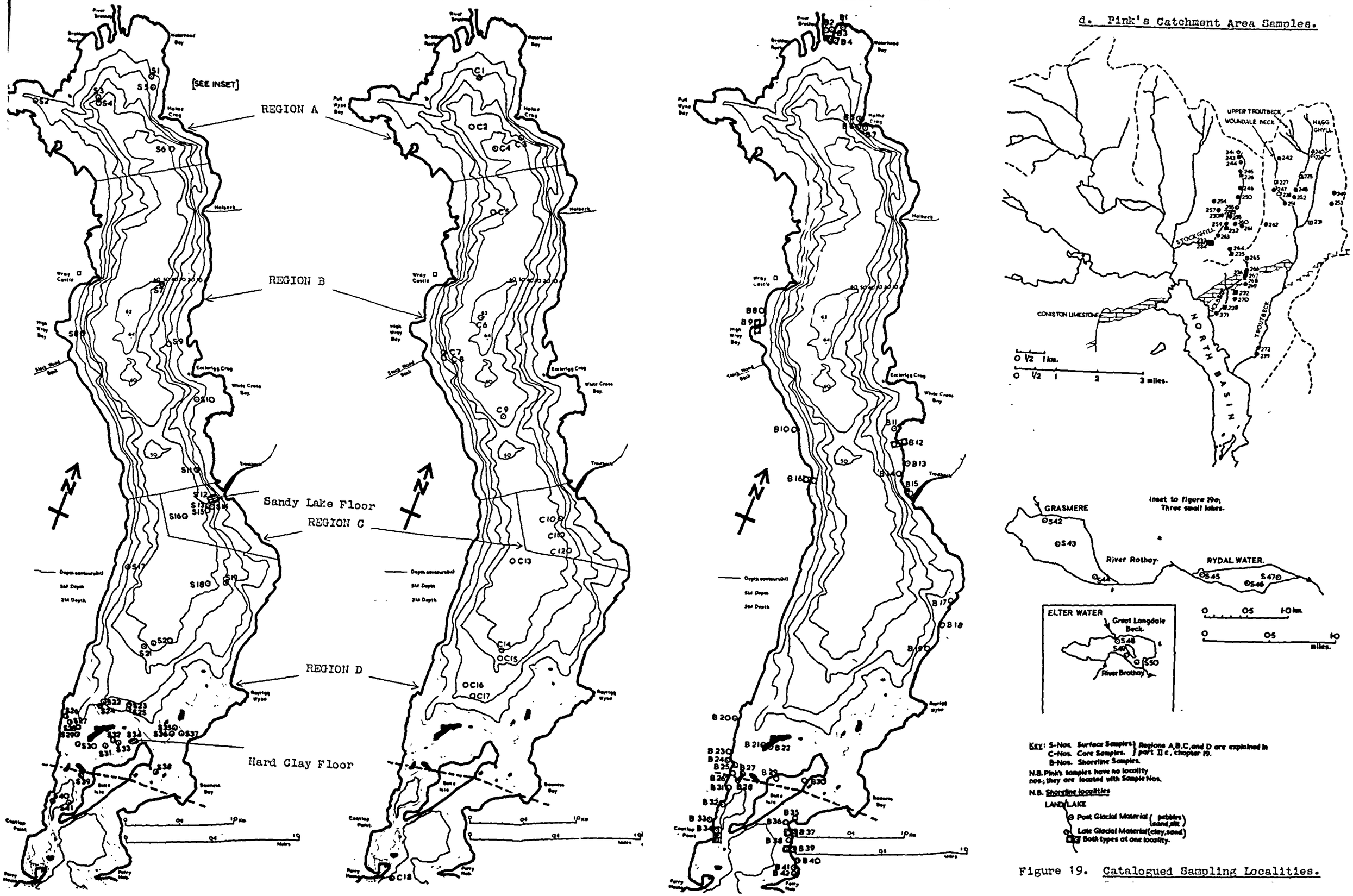
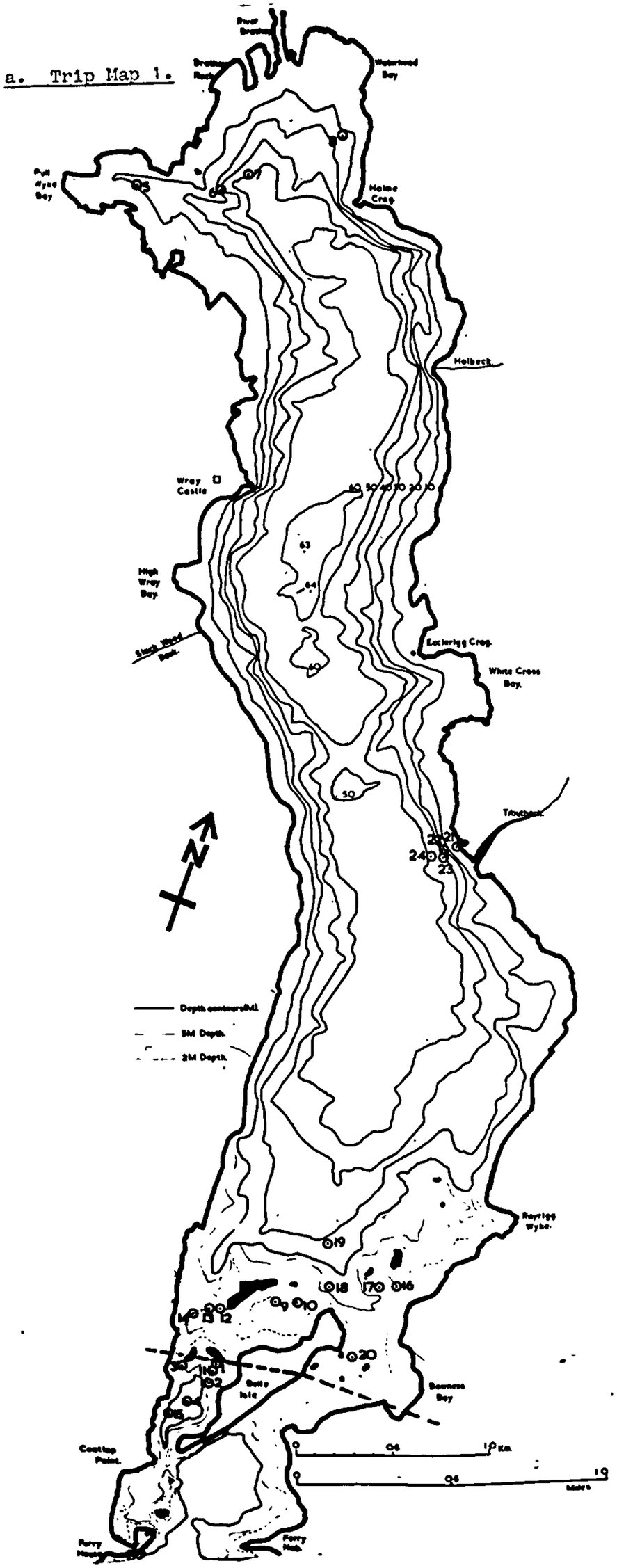


Figure 19. Catalogued Sampling Localities.

a. Trip Map 1.



b. Trip Map 2.

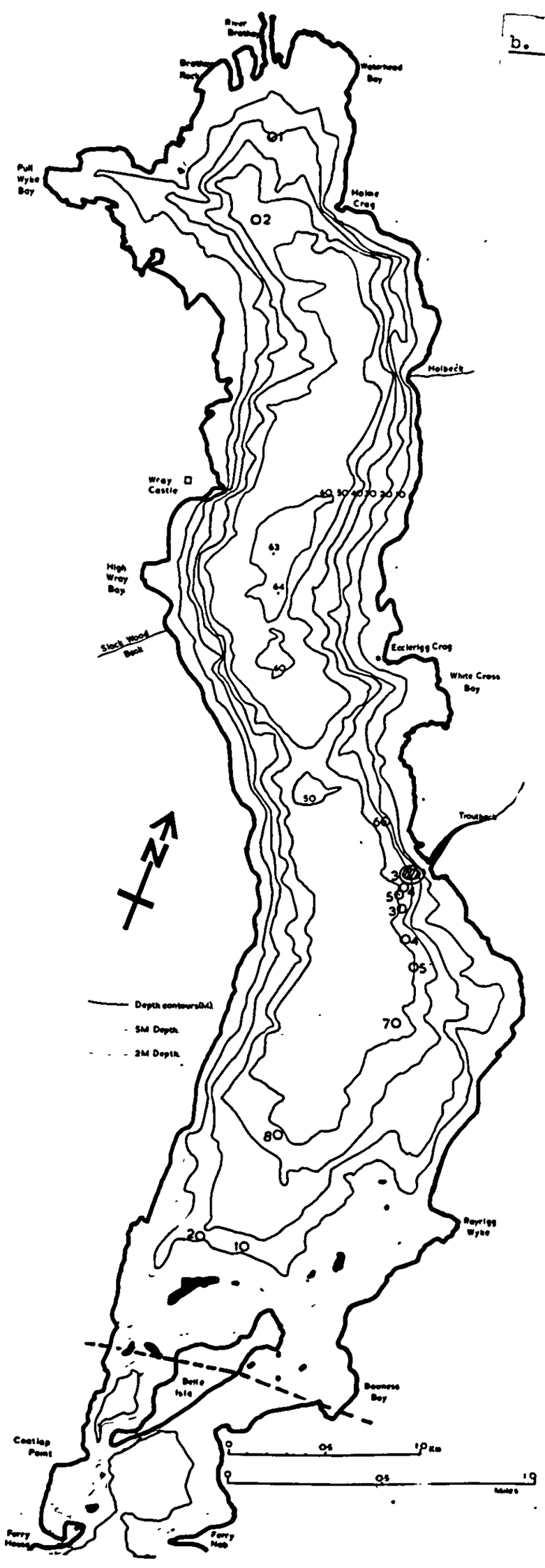
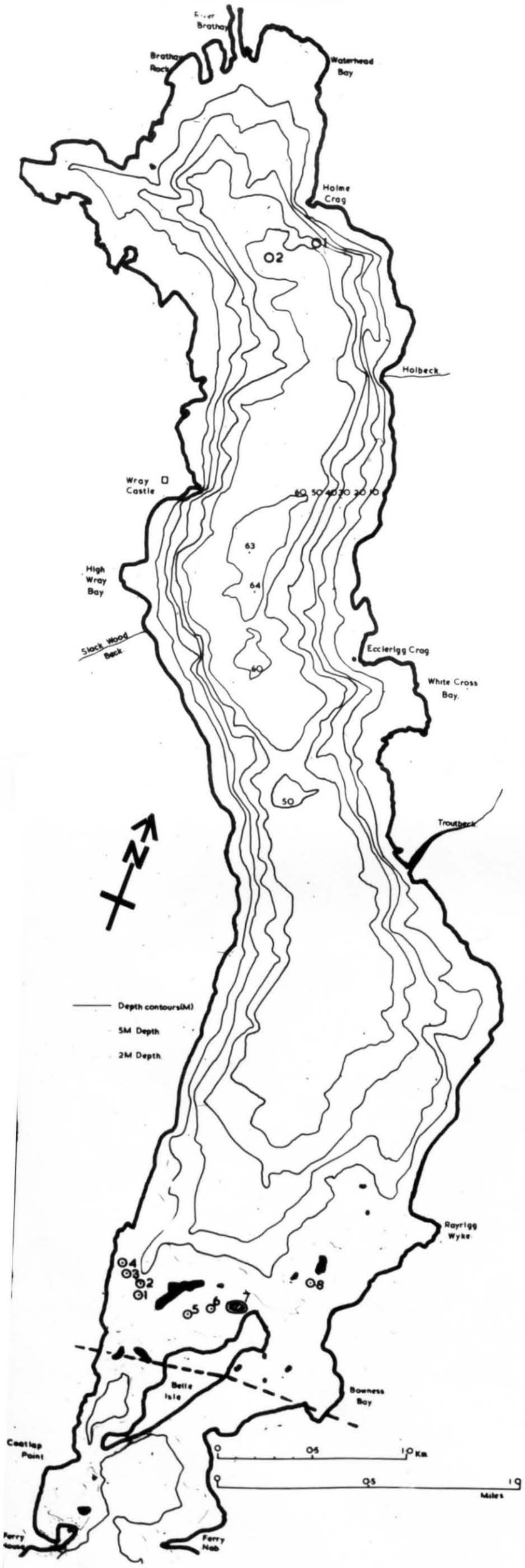


Figure 1. Field Sampling Localities.

c. Trip Map 3.



d. Trip Map 4, Showing Surveyed Shoreline Features.

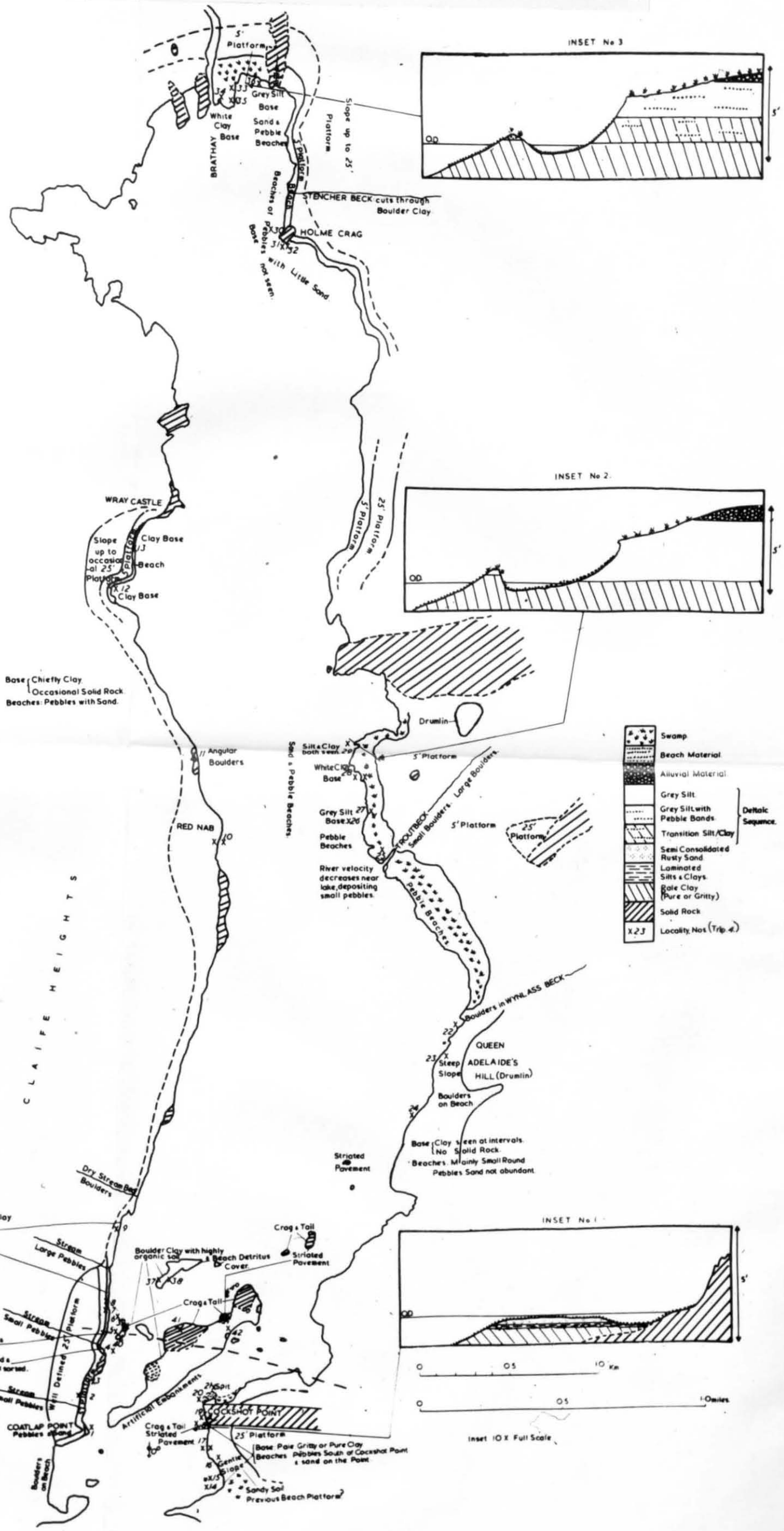
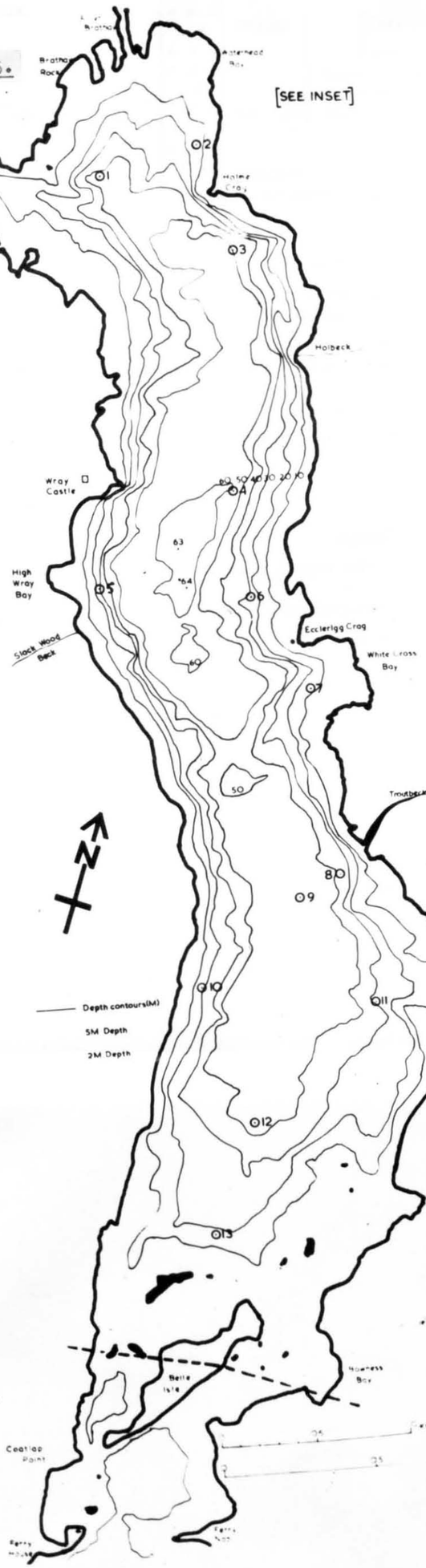
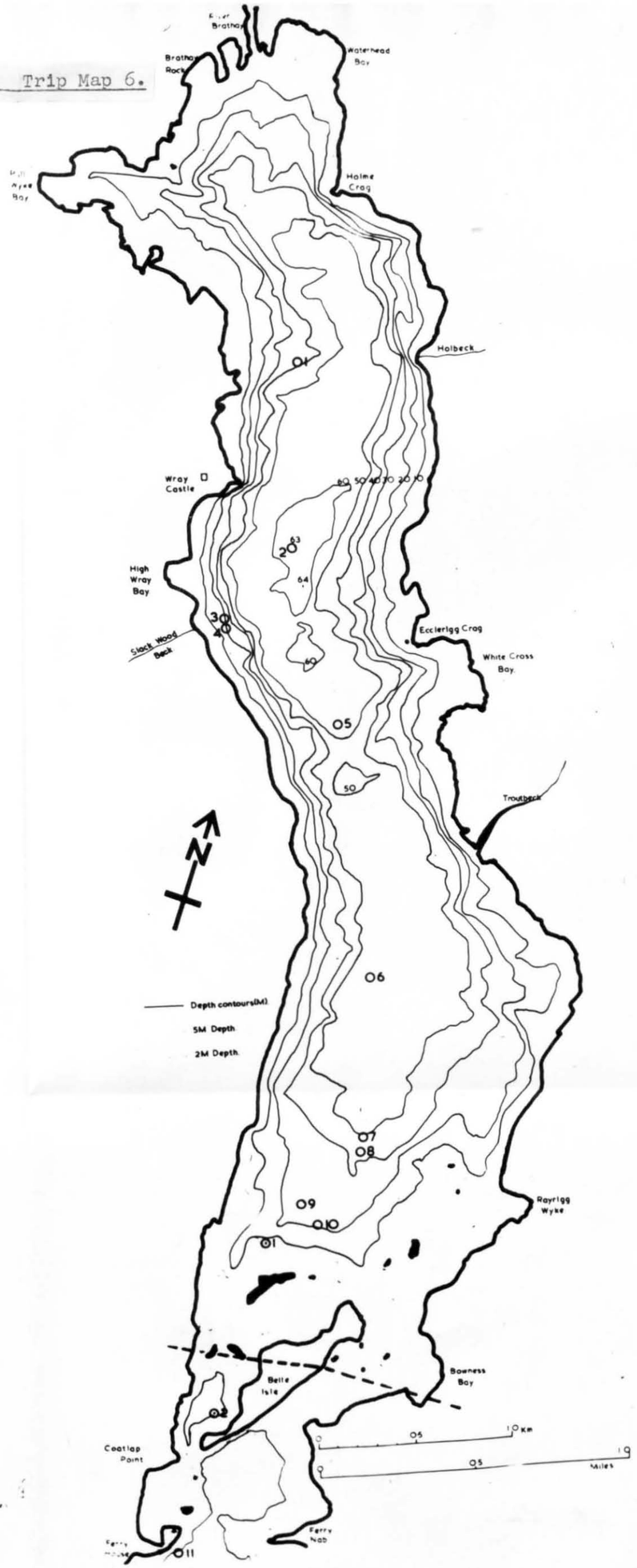


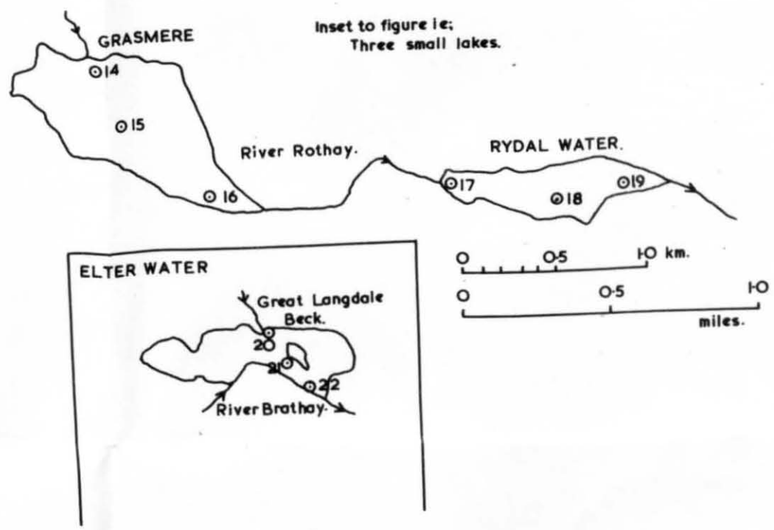
Figure 1 continued.

e. Trip Map 5.



f. Trip Map 6.





Inset to figure 1e;
Three small lakes.

Key ⊙ Surface sampling localities (S-Nos.)
O Core sampling localities (C-Nos.)
X Shoreline sampling localities (B-Nos.)

Figure 1 continued.

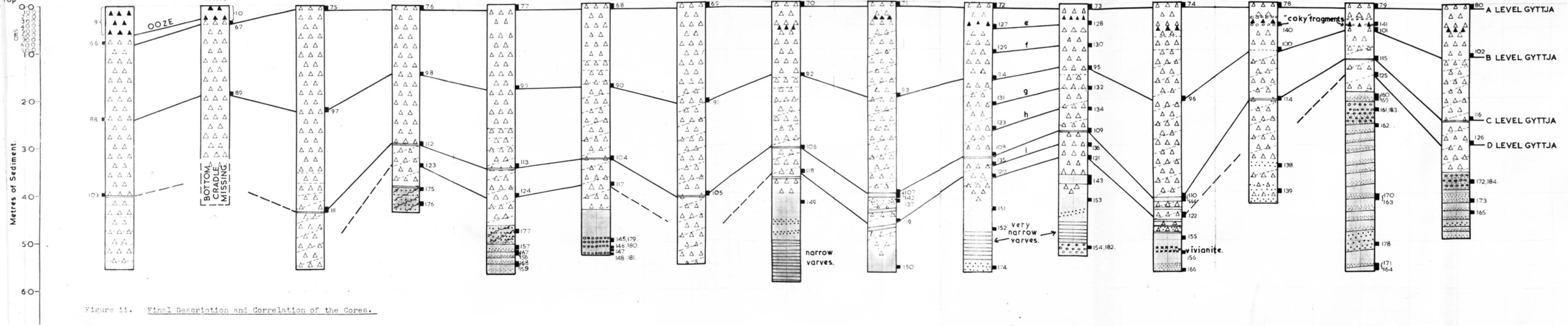


Figure 11. Final Description and Correlation of the Cores.

KEY

OOZE
GYTTJA
[Cores nos. 14, 16, 18, 19, 20 were not examined.
These are not the same symbols as those used in the main part of the thesis.
BANDING
CLAY BAND IN GYTTJA (Horizontal or Dipping)
SANDY LAYER
SHARP BOUNDARY CLAY/GYTTJA
CLAY (PINK)
SAND (LIGHT GREY AND FRIABLE)
SILT (DARK GREY)
PEBBLES
BANDING IN ANY FACIES

"Chronological" correlation lines.
97 Sample nos. at measured depth in cores.
167/58 Two adjacent samples.
145, 179. Two sample nos. from one sample. (pebble layers)